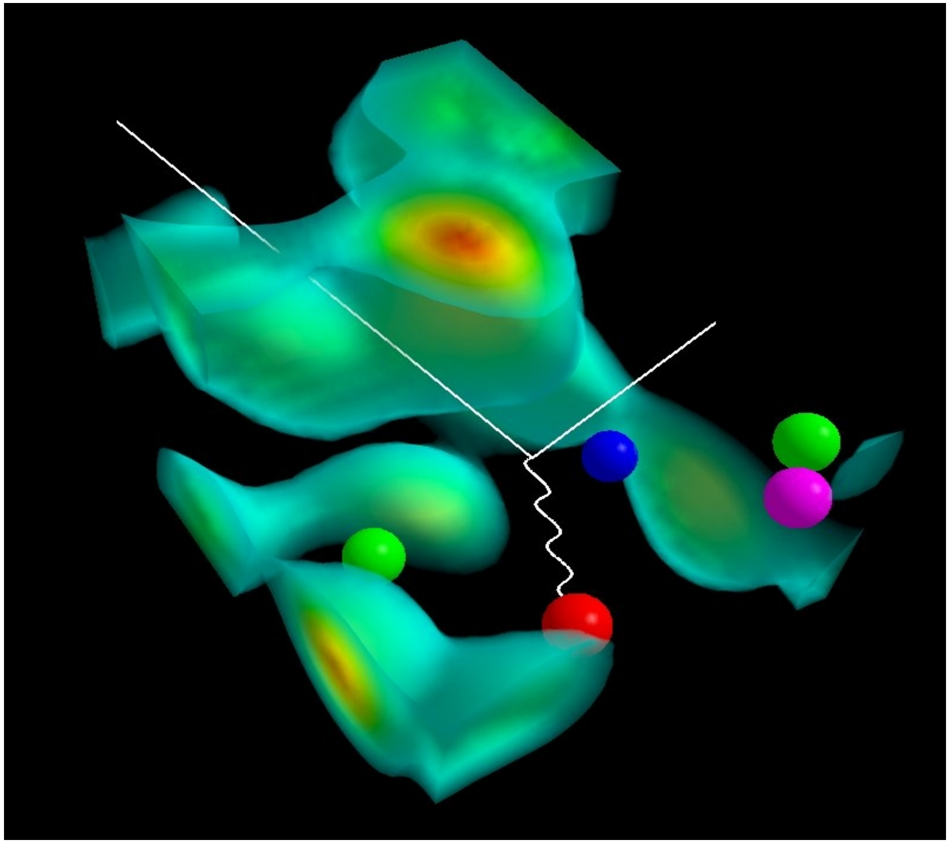
Hadron Structure: Free and in-Medium



Anthony W. Thomas

APCTP Focus Program in Nuclear Physics
Korea: July 14th 2021

A Fascinating Program

- QCD: q-g-g vertices from lattice; 2-flavor dense matter
- EMC effect
- Baryon form factors
- Meson structure versus quark mass and in-medium
- Mesic atoms; exotic states (tetra-quarks and penta-quarks)
- Holographic QCD
- Neutron stars: strangeness; dark matter; quarkyonic matter…

Distribution Amplitudes for Pseudoscalar Mesons

- **Study of Serna et al., using Bethe-Salpeter ladder approximation with flavor dependent dressing functions**

Eur. Phys. J. C (2020) 80:955 Page 13 of 18 955

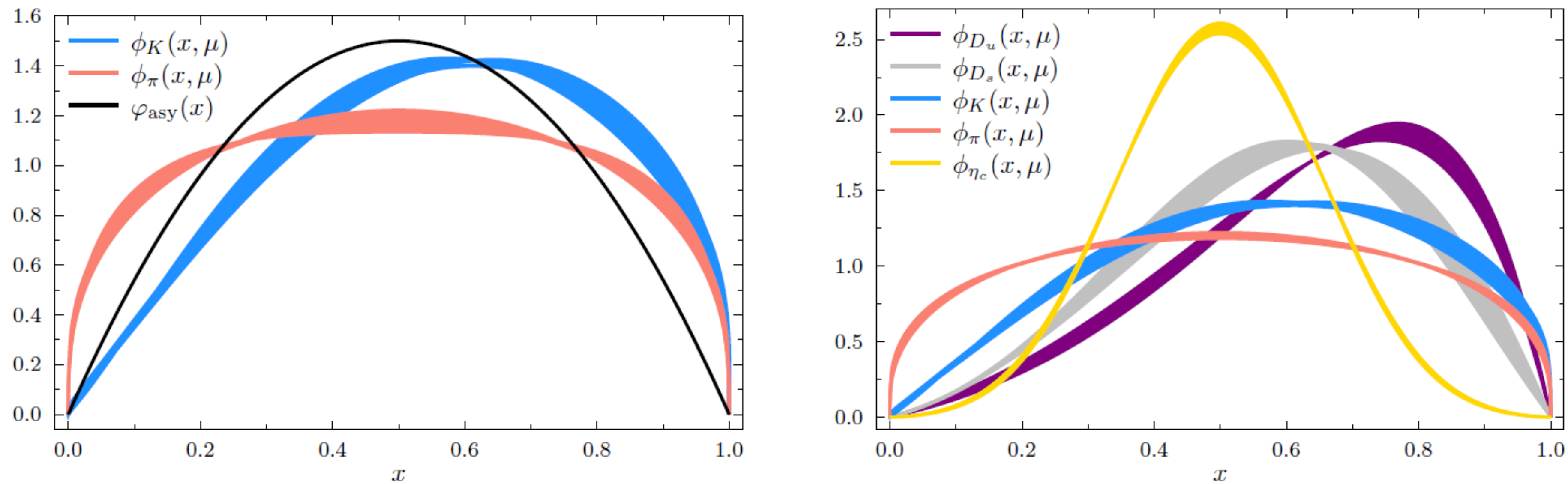
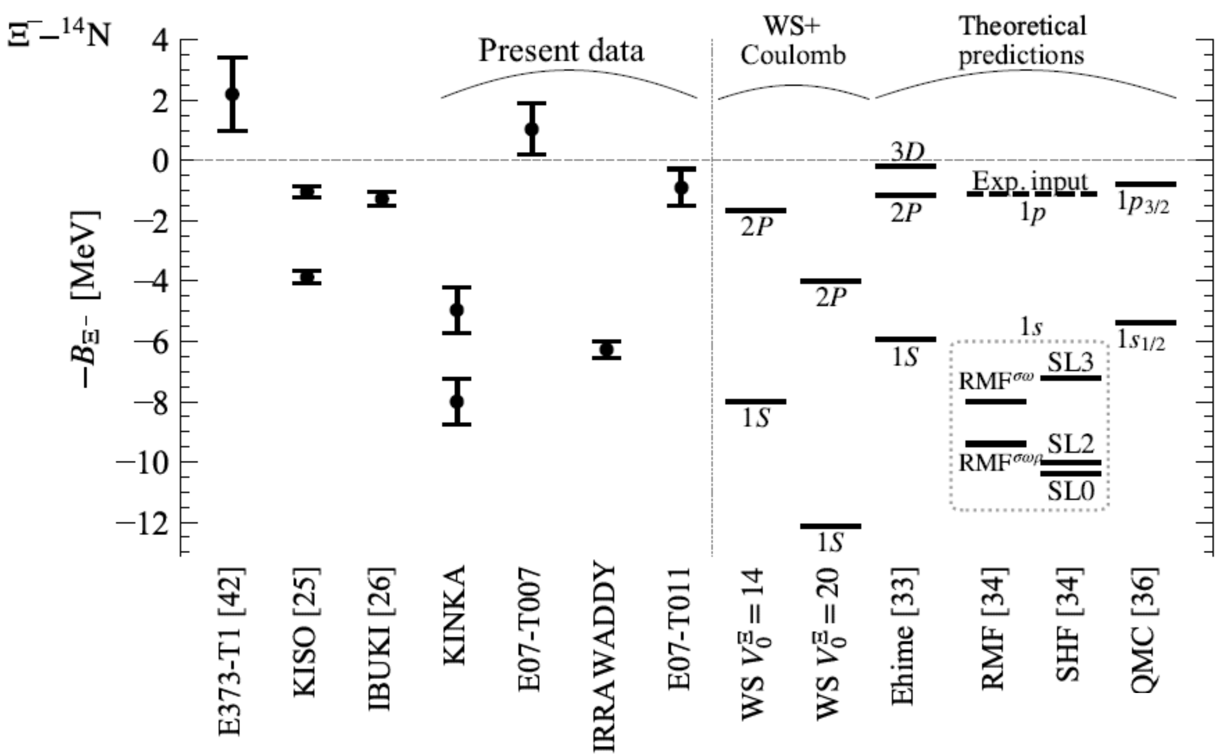


Fig. 5 Distribution amplitudes on the light front at a renormalization point $\mu = 2$ GeV. Left panel: $\phi_\pi(x,\mu)$, $\phi_K(x,\mu)$ and $\phi_{\text{asy}}(x) = 6x\bar{x}$ is the asymptotic LCDA. Right panel: Comparison of the light-meson distribution amplitudes with $\phi_{D_u}(x,\mu)$, $\phi_{D_s}(x,\mu)$ and $\phi_{\eta_c}(x,\mu)$. The error bands correspond to uncertainties of $\omega_f \pm \Delta\omega_f$ in the interaction model

Ξ Hypernuclei

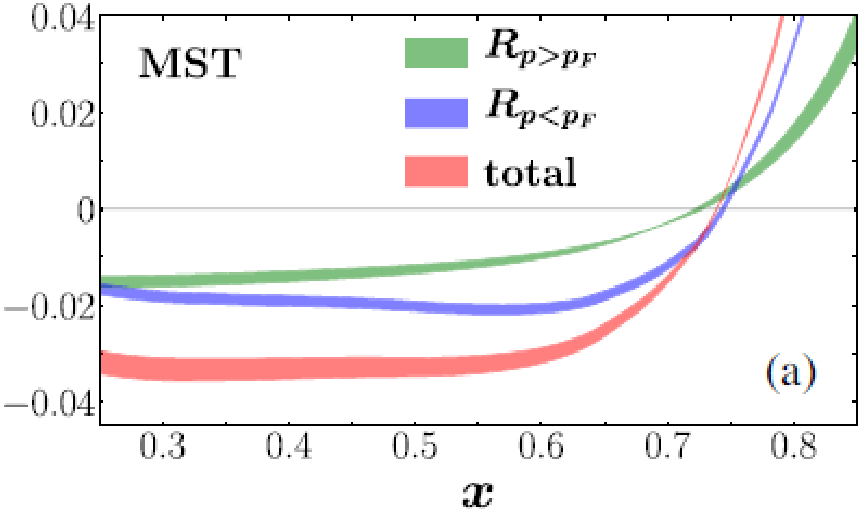
First observation of a nuclear *s*-state of Ξ hypernucleus, $^{15}_{\Xi}\mathrm{C}$



Vital importance for neutron star EoS

arXiv:2103.08793, Yoshimoto *et al*.

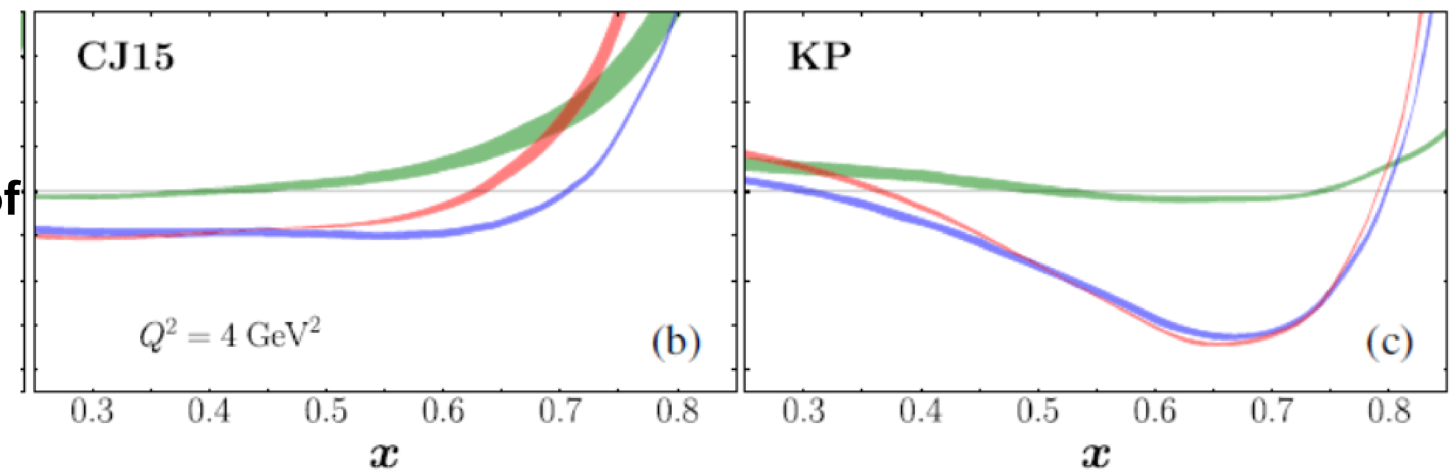
Wang: Study of the EMC effect in the deuteron



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

p_F = 300 MeV/c

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



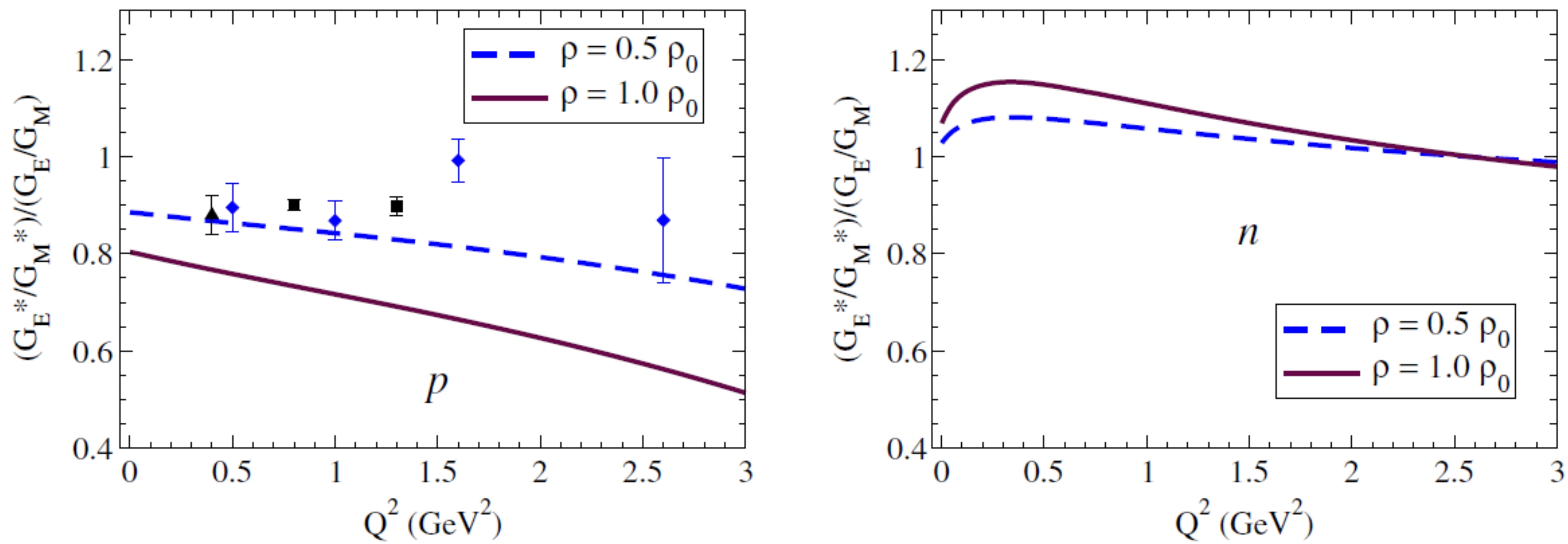
Wang *et al.*, Phys Rev Lett 125 (2020) 262002

Baryon form factors in-medium

Octet baryon electromagnetic form factor double ratios $(G_E^*/G_M^*)/(G_E/G_M)$ in a nuclear medium

G. Ramalho, J. P. B. C. de Melo, and K. Tsushima

OCTET BARYON ELECTROMAGNETIC FORM FACTOR DOUBLE … PHYS. REV. D **100,** 014030 (2019)



- **Also computed other octet baryons**

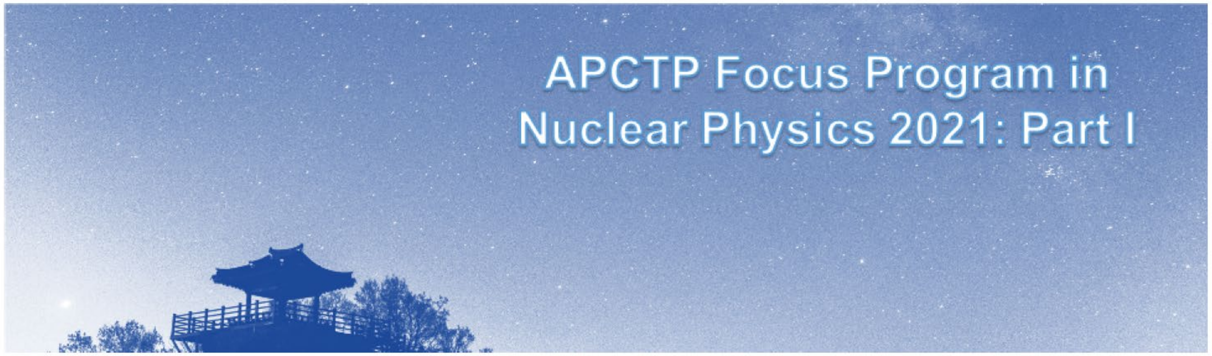
My focus: Hadron Structure Free and In-Medium??

I. Why even ask this question?

− Should not: “standard model of nuclear physics” and EFT

− Should: EMC effect; Coulomb sum-rule; chiral restoration; percolation; transition to quark matter at high density; very large scalar and vector mean-fields in nuclei

2. Relevance to JLab at 12GeV, J-PARC, FAIR and the EIC(s)
and
Neutron Stars



APCTP Focus Program in Nuclear Physics 2021 Part I: Hadron properties in a nuclear medium from the quark and gluon degrees of freedom

QCD

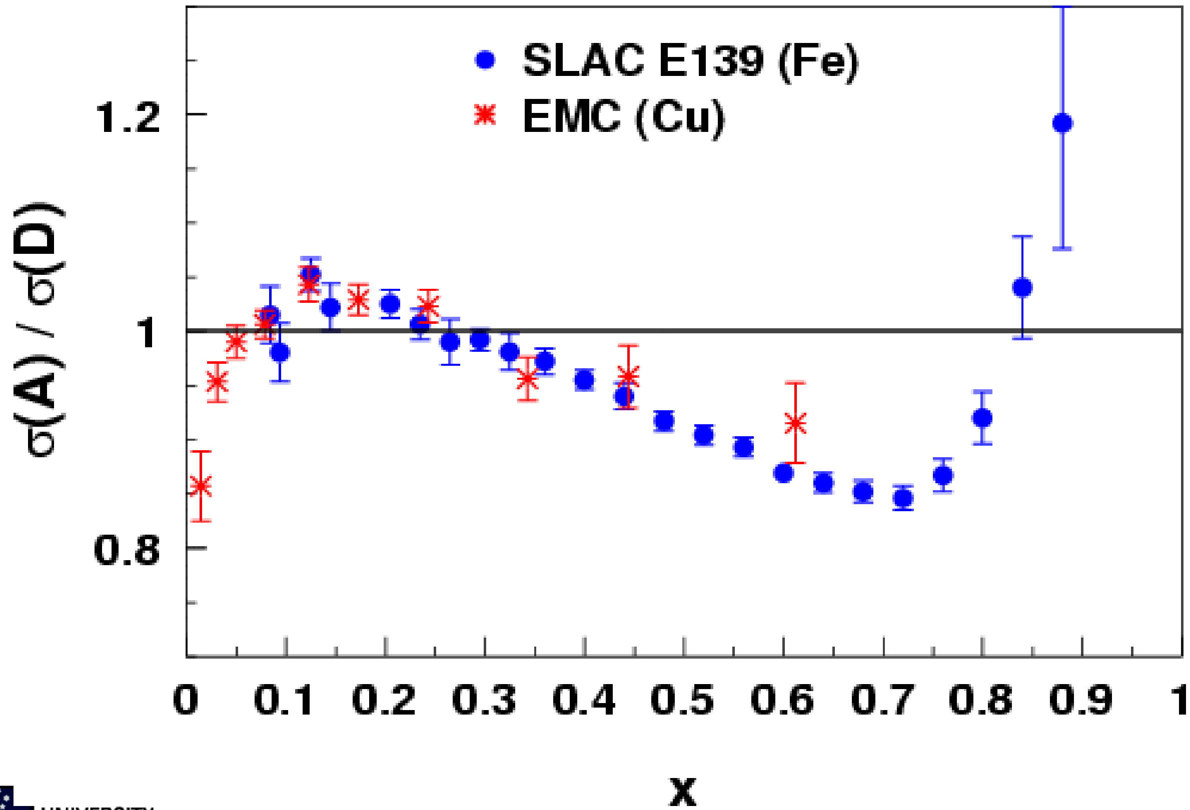
- Discovered: early 1970s
- Constituent quark and bag models: mid-70s
- Plus chiral symmetry: cloudy bag model late 70s and early-80s
- Quarks in individual nucleons occupy a large fraction of the volume of a nucleus – possible percolation; multi-quark fluctuations…
- Then two major experimental surprises strongly suggested a change in structure for bound nucleons

The European Muon Collaboration (EMC) Effect

The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the
  HEP and Nuclear communities 38 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)

Coulomb Sum-Rule

Coulomb Sum Rule for ^{40}Ca, ^{48}Ca, and ^{56}Fe for $|\vec{q}| \leq 550$ MeV/c

Coulomb sum rule was computed and shows a suppression of 30% for ^{40}Ca and of 20% for both ^{48}Ca and ^{56}Fe at a momentum transfer greater than twice the Fermi momentum. We have observed a

TRANSVERSE AND LONGITUDINAL RESPONSE FUNCTIONS IN QUASIELASTIC ELECTRON SCATTERING FROM NUCLEI

Zein-Eddine MEZIANI

Dept. of Physics, University of Virginia, Charlottesville, VA 22901*

Transverse and longitudinal response functions have been extracted for ^{3}He, ^{12}C, ^{40}Ca, ^{48}Ca, and ^{56}Fe up to a momentum transfer of 550 MeV/c. The quenching of the longitudinal response function in the quasi-elastic region is significant and might be a signature of modification of the intrinsic properties of the nucleon in nuclear matter.

Theoretical agreement with this interpretation: Noble, Celenza *et al.*, *Mulders, Ericson et al., Brown and Rho………*

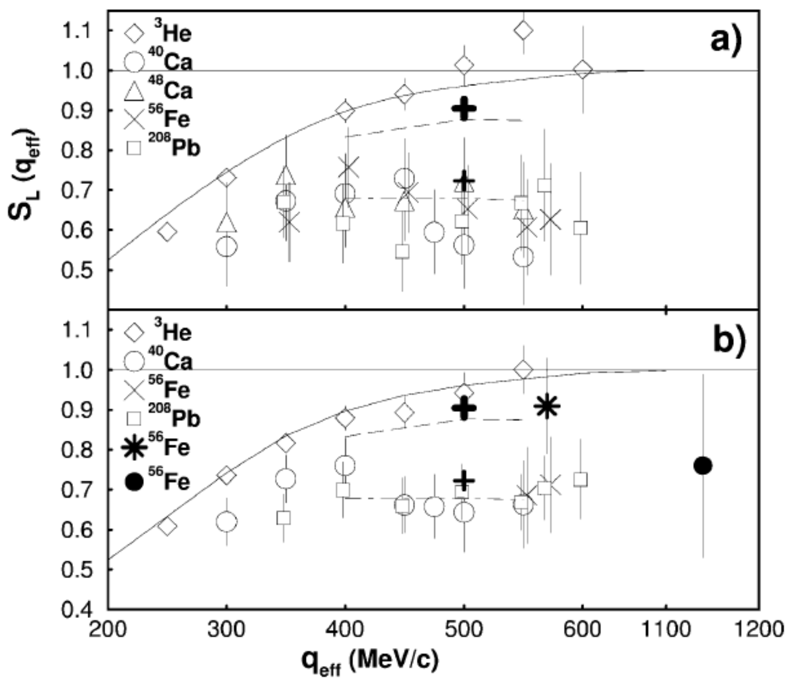
Physics Letters B 515 (2001) 269–275

www.el

Is the Coulomb sum rule violated in nuclei?

J. Morgenstern [a], Z.-E. Meziani [b]

- **New measurements and careful treatment of Coulomb distortion**



In conclusion, there is a good agreement between the data from Saclay, SLAC, Bates 180° experiments and Bates data taken with the new setup. We believe that we have established experimentally the existence of a quenching of S_L in medium and heavy nuclei as shown in Fig. 6. This quenching is not observed in low-density nuclei such as ^{3}He and ^{2}D [11,18] and short-range correlations are not able to explain this effect. We interpret this as an indication for a change of the nucleon properties inside the nuclear medium. If we assume the dipole expression for the charge form factor, the observed quenching of the CSR would correspond to a relative change of the proton charge radius of 13 ± 4% in a heavy nucleus. The accuracy of the CSR could be improved and the q region extended up to 1 GeV/c with the new generation of electron accelerators. Such a proposal has been approved recently at Jefferson Lab [51].

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These results potentially offer:

New Insight into the question:
What is the atomic nucleus?

There are two very different extremes….

Quark Structure matters/doesn't matter

- **Nuclear femtography: the science of mapping the quark and gluon structure of *atomic nuclei* is just beginning, with new experimental facilities**

  OR

- **"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"**

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS
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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!!**

Just one example of very large scalar mean-fields

TABLE II. Results of a relativistic Dirac-Brueckner calculation in comparison to the tential B. As a function of the Fermi momentum k_F, it is listed: the energy per nucleon vector potentials U_S and U_V, and the wound integral κ.

		Relativistic			
k_F (fm^{-1})	$\mathcal{E}/A$ (MeV)	$\tilde{M}/M$	U_S (MeV)	U_V (MeV)	κ (%)
0.8	−7.02	0.855	−136.2	104.0	23.1
0.9	−8.58	0.814	−174.2	134.1	18.8
1.0	−10.06	0.774	−212.2	164.2	16.1
1.1	−11.18	0.732	−251.3	195.5	12.7
1.2	−12.35	0.691	−290.4	225.8	11.9
1.3	−13.35	0.646	−332.7	259.3	12.5
1.35	−13.55	0.621	−355.9	278.4	13.0
1.4	−13.53	0.601	−374.3	293.4	13.8
1.5	−12.15	0.559	−413.6	328.4	14.4
1.6	−8.46	0.515	−455.2	371.0	15.8

Brockmann and Machleidt, Phys Rev C52 (1990) 1965

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

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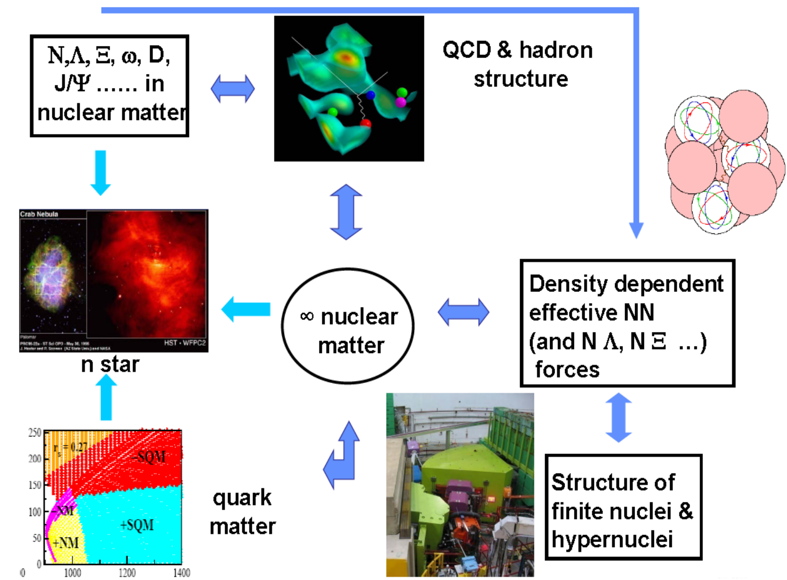
Suggests a different approach : QMC Model

(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 4 parameters**

  (m_σ , $g^{\sigma,\omega,\rho}{}_q$)

  – 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**

Self-consistent solution for confined quarks in a hadron in nuclear matter

$$[i\gamma^\mu \partial_\mu - (m_q - g_\sigma{}^q \bar{\sigma}) - \gamma^0 g_\omega{}^q \bar{\omega}]\psi = 0$$

Source of σ changes: $\int_{Bag} d\vec{r}\,\bar{\psi}(\vec{r})\psi(\vec{r})$

SELF-CONSISTENCY

and hence mean scalar field changes…

and hence quark wave function changes….

THIS PROVIDES A NATURAL SATURATION MECHANISM (VERY EFFICIENT BECAUSE QUARKS ARE LIGHT)

source is suppressed as mean scalar field increases (i.e. as density increases)

Quark-Meson Coupling Model (QMC):
Role of the Scalar Polarizability of the Nucleon

The response of the nucleon internal structure to the scalar field is of great interest… and importance

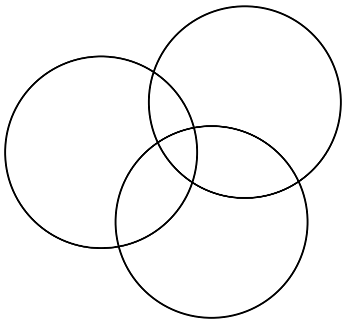
$$M^*(\vec{r}) = M - g_\sigma \sigma(\vec{r}) + \frac{d}{2}\left(g_\sigma \sigma(\vec{r})\right)^2$$

Non-linear dependence through the scalar polarizability
d ~ 0.22 R in original QMC (MIT bag)

Indeed, in nuclear matter at mean-field level, this is the ONLY place the response of the internal structure of the nucleon enters.

Scalar Polarizability ≡ Many-Body Forces

- **Consequence of polarizability in atomic physics is many-body forces:**



$$V = V_{12} + V_{23} + V_{13} + V_{123}$$

  - **same is true in nuclear physics**

- **Three-body forces generated with NO new parameters**

Application to nuclear structure

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

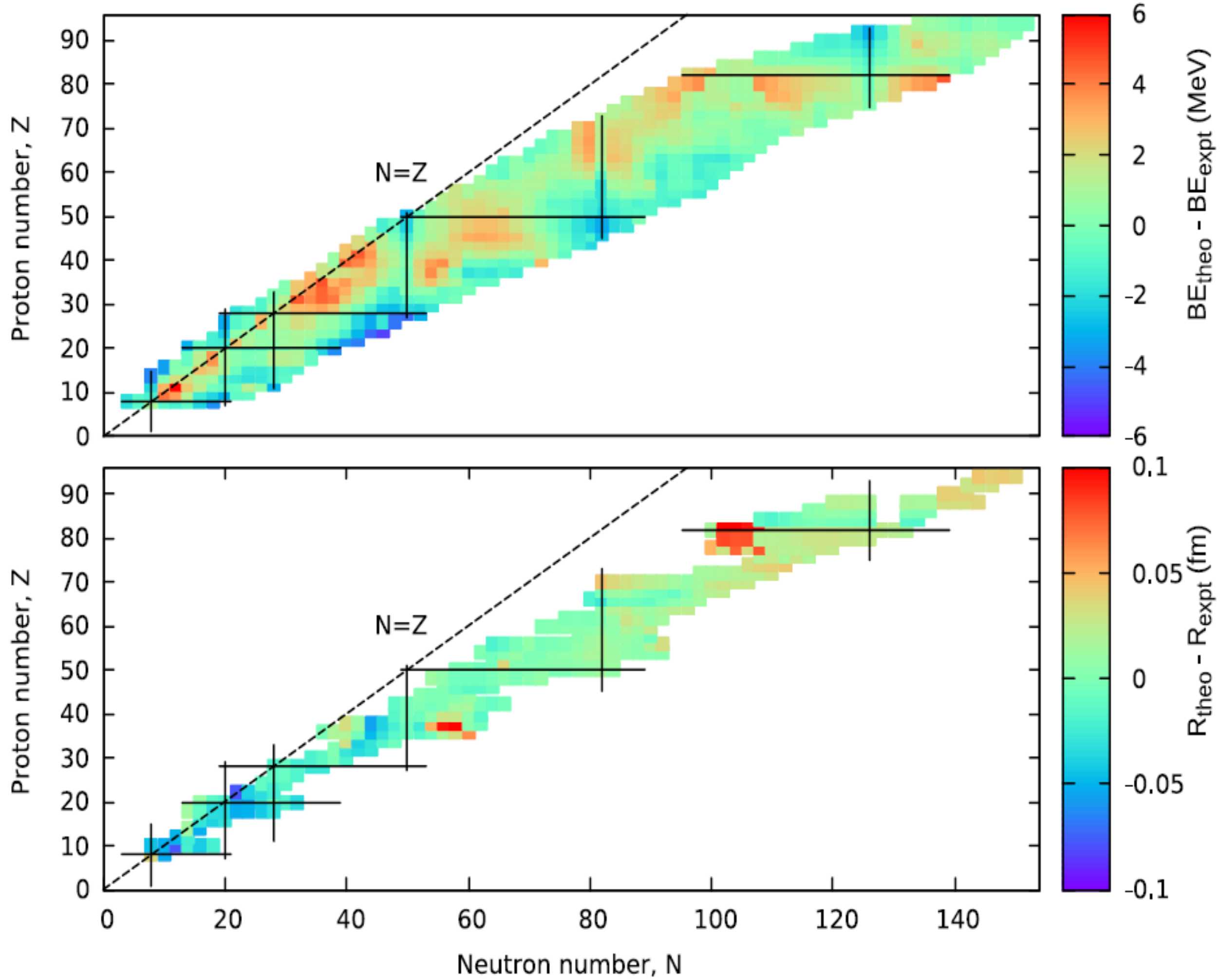
- **Start with classical theory of MIT-bag nucleons with structure modified in medium to give M_{eff} (σ).**
- **Quantise nucleon motion (non-relativistic), expand in powers of derivatives**
- **Derive equivalent, local energy functional:**

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

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)

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Giant Monopole Resonances

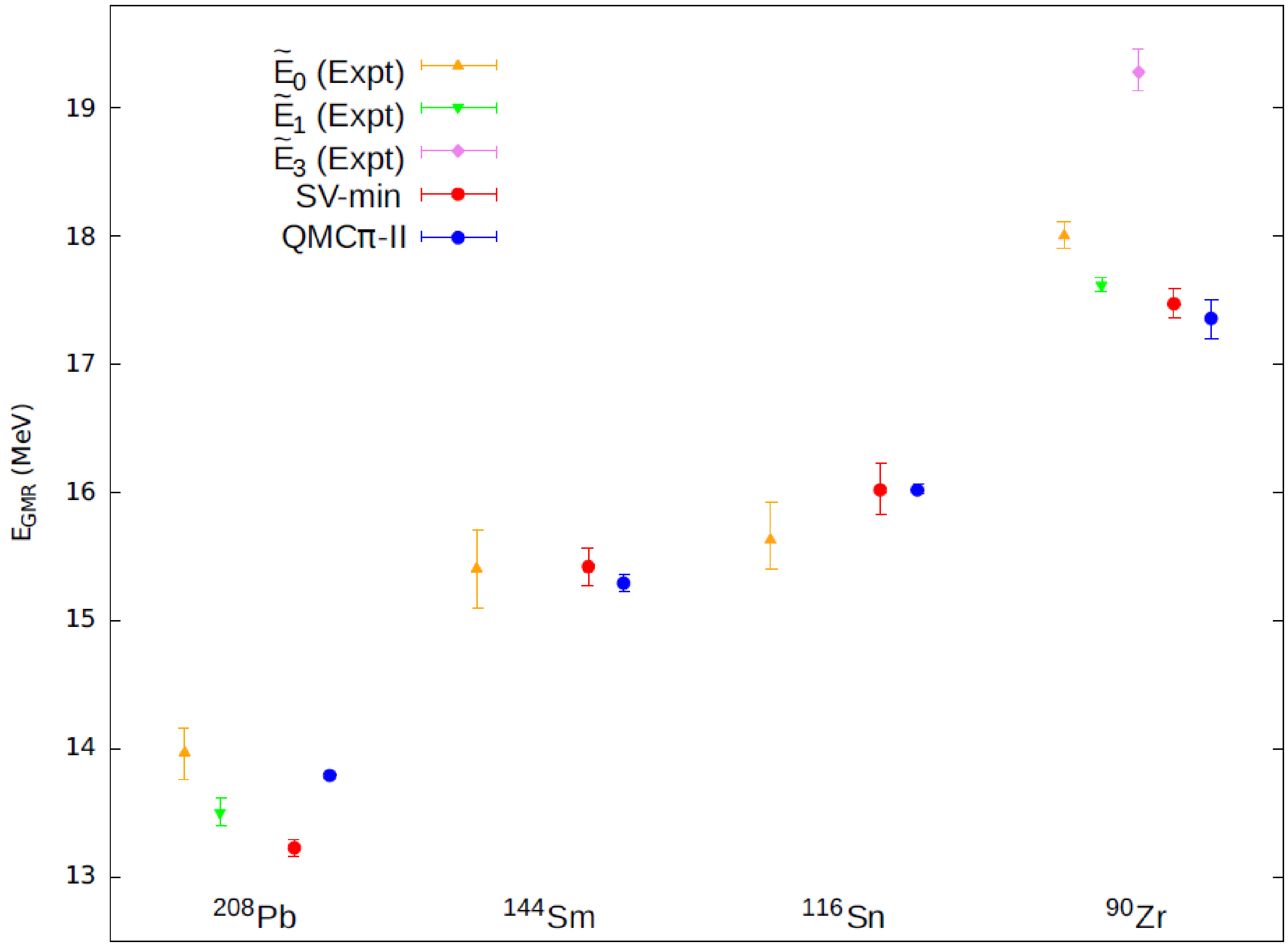
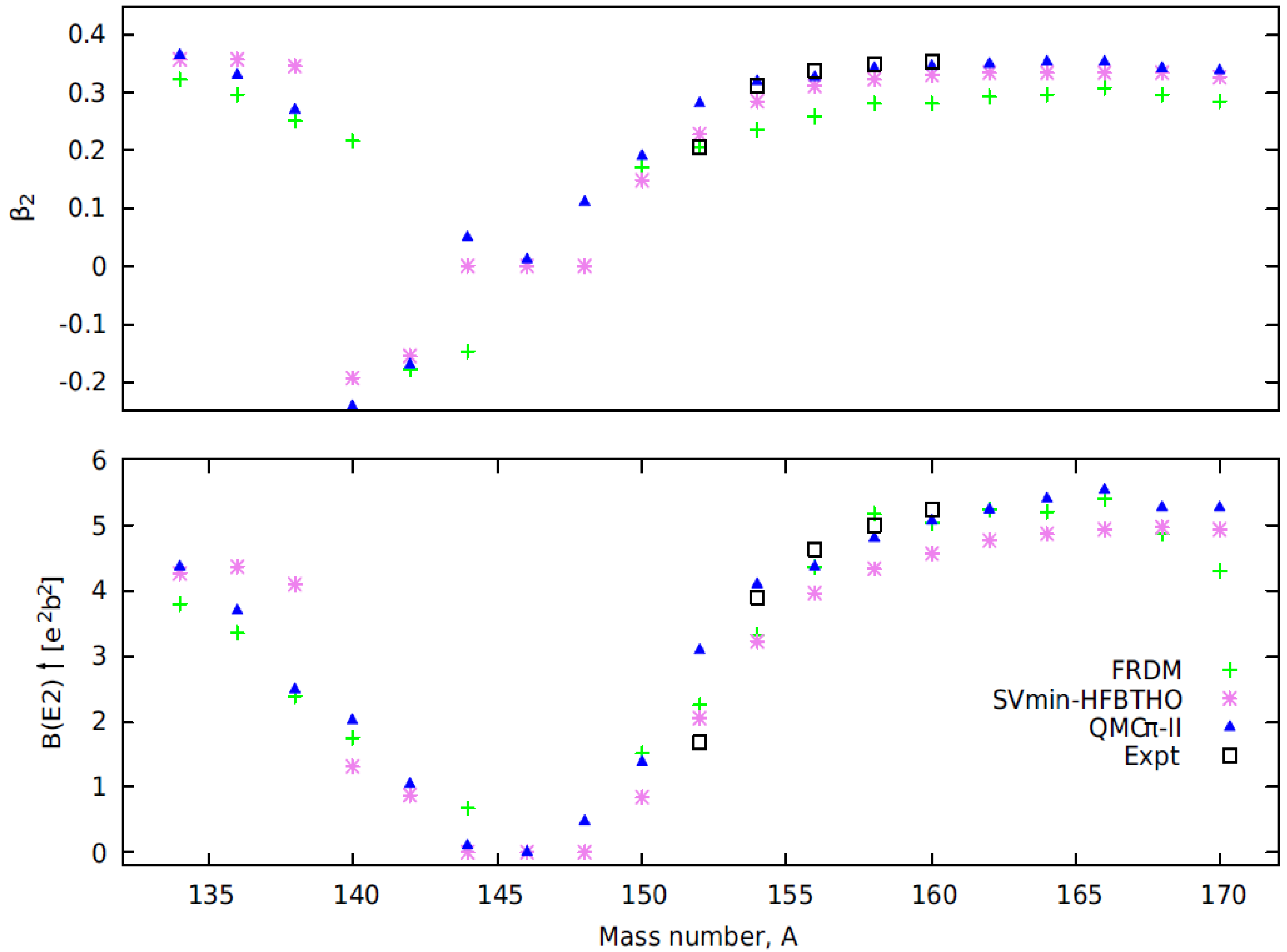


FIG. 13. GMR energies for ^{208}Pb, ^{144}Sm, ^{116}Sn, and ^{90}Zr from experiment and for the QMCπ-II and SVmin models. Experimental data are taken from Table 1 of Ref. [24].

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

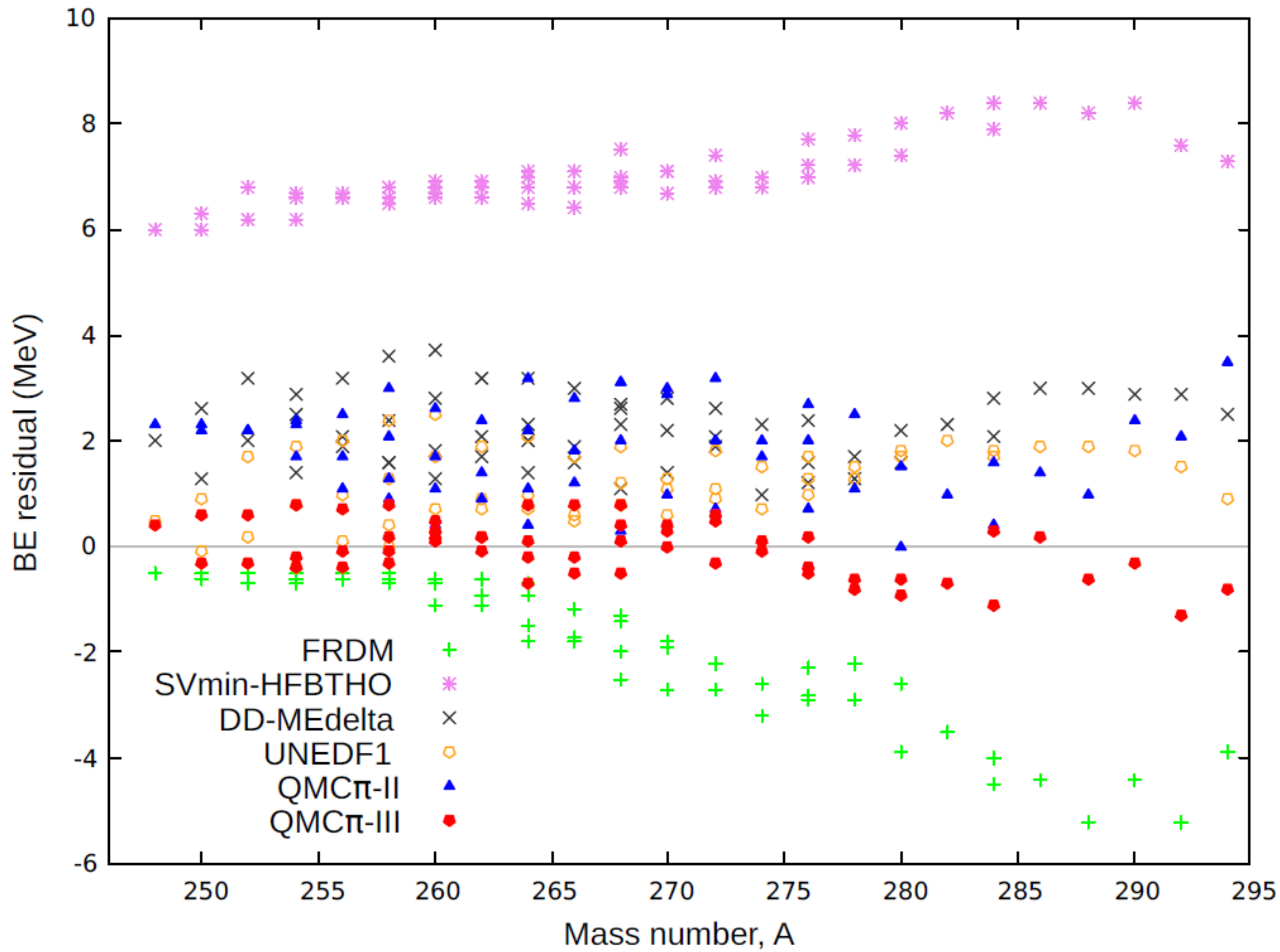
Deformation Good: e.g. Gd (Z=64) isotopes



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

Superheavy Nuclei Z ≥ 100

For QMCπ-III binding energies reproduced at better than 0.1%



To be published – model details in Martinez et al., Phys Rev C102, 034304 (2020)

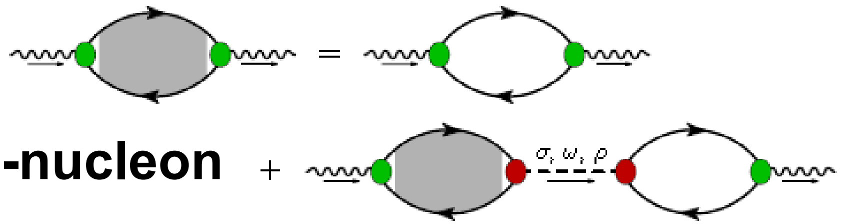
Modified Electromagnetic Form Factors In-Medium

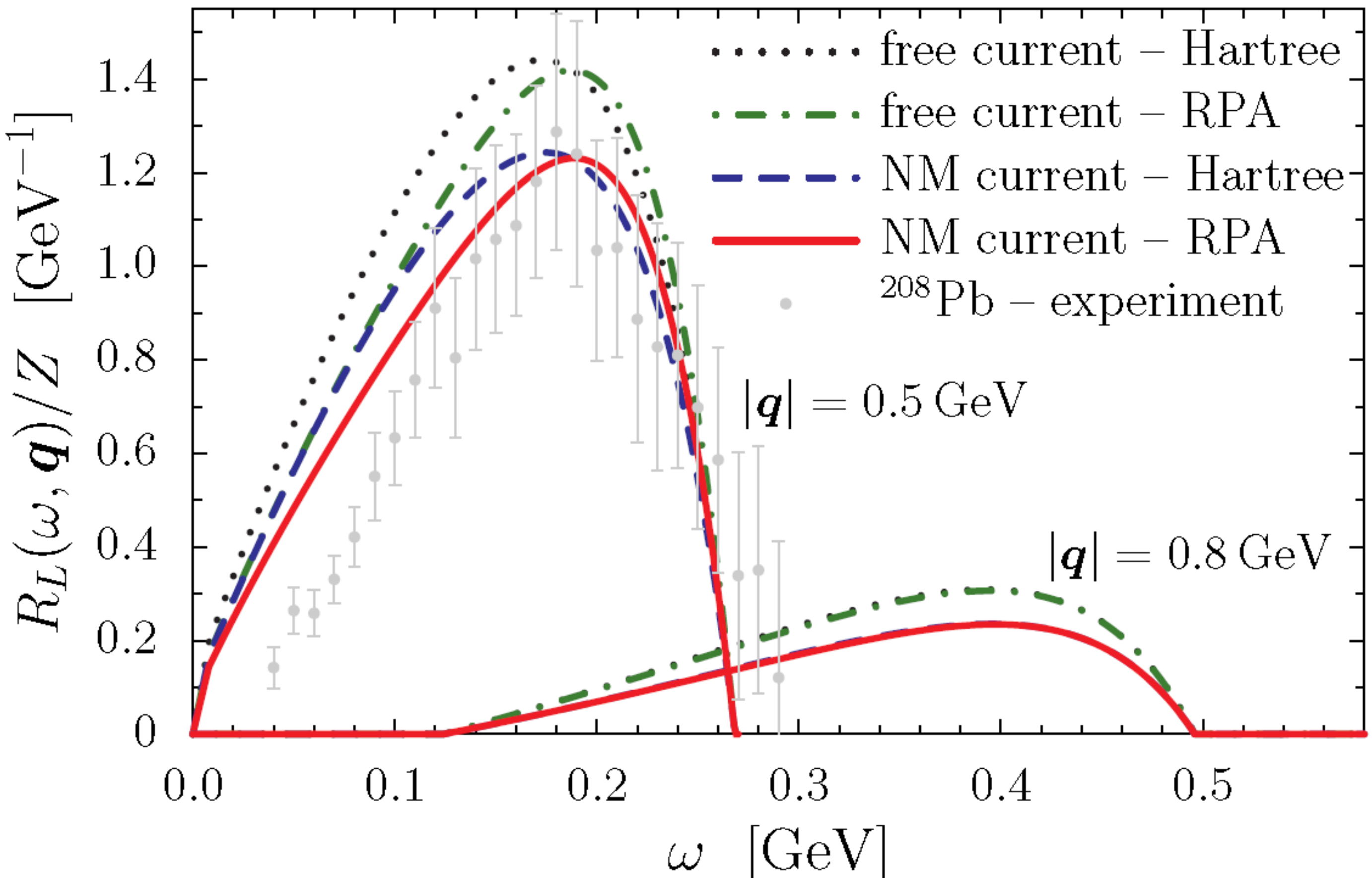
Response Function

$$\frac{d^2\sigma}{d\Omega\, d\omega} = \sigma_{\mathrm{Mott}}\left[\frac{q^4}{|\boldsymbol{q}|^4} R_L(\omega, |\boldsymbol{q}|) + \left(\frac{q^2}{2|\boldsymbol{q}|^2} + \tan^2\frac{\theta}{2}\right) R_T(\omega, |\boldsymbol{q}|)\right]$$

RPA correlations repulsive

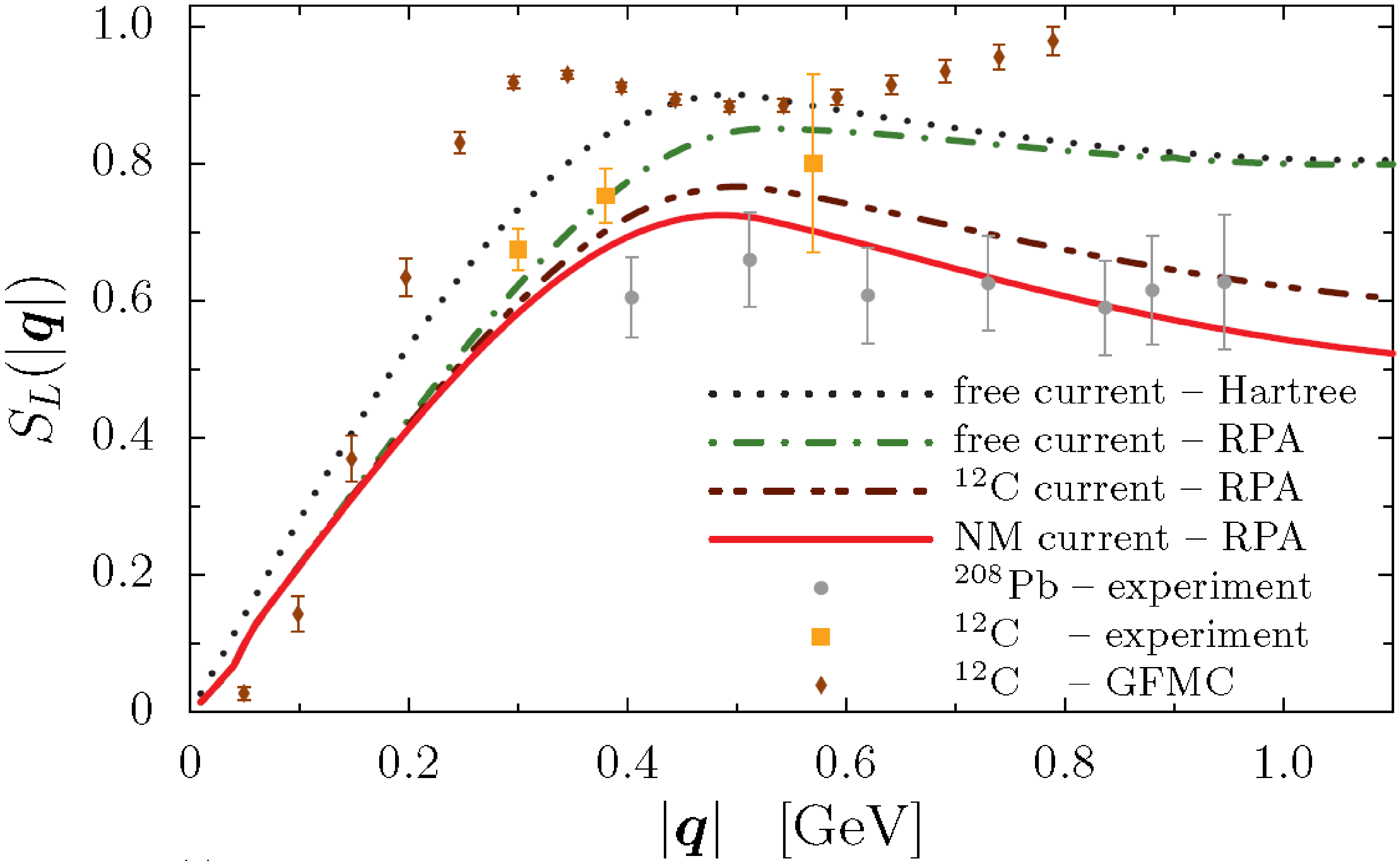
Significant reduction in Response Function from the modification of bound-nucleon





Cloët, Bentz & Thomas, PRL 116 (2016) 032701

Comparison with Unmodified Nucleon & Data



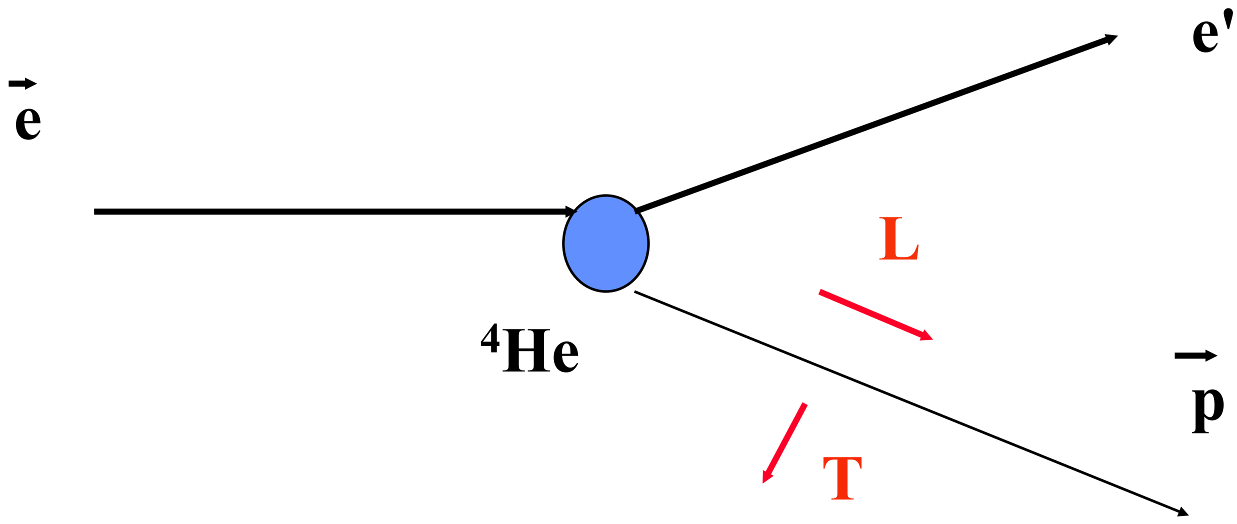
$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|q|} d\omega \, \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)}$$

Data: Morgenstern & Meziani

Calculations: Cloët, Bentz & Thomas (PRL 116 (2016) 032701)

Experimental Test at Mainz & JLab*

Capacity to measure polarization in coincidence:



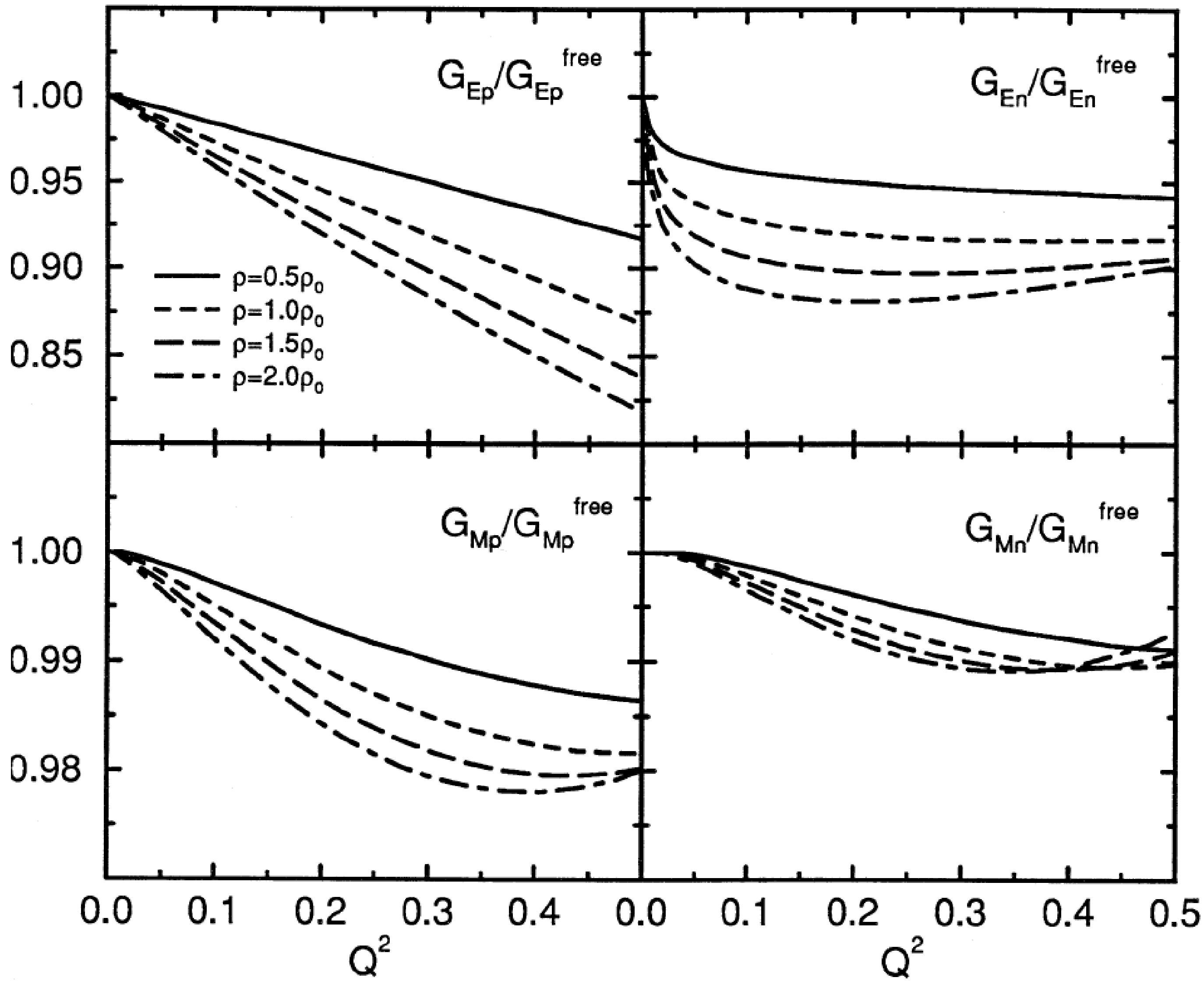
$\sigma_T / \sigma_L \sim G_E/G_M$: Compare ratio in ^{4}He and in free space

S. Dieterich *et al.* , Phys. Lett. B500 (2001) 47; and JLab report 2002

Archival

In-medium electron-nucleon scattering

D.H. Lu [a], A.W. Thomas [a], K. Tsushima [a], A.G. Williams [a], K. Saito



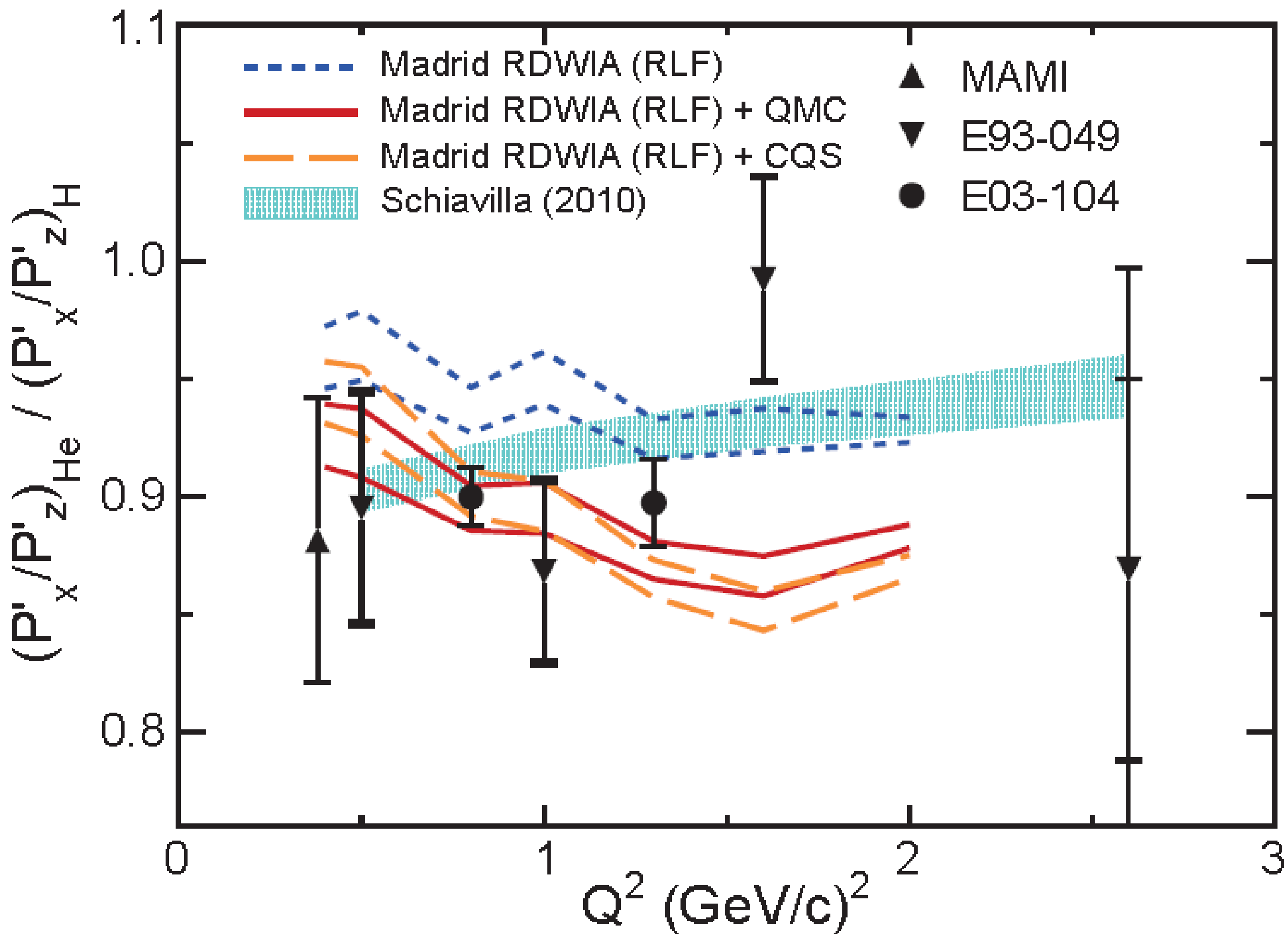
QMC

Physics Letters B 417 (1998) 217–223

Jefferson Lab & Mainz

Polarized $^4He(e,e'p)$ measuring recoil p polarization (T/L : G_E/G_M)

Strauch et al., EPJ Web of Conf. 36 (2012) 00016



QMC medium effect predicted more than a decade years before the experiment (D.H. Lu et al., Phys. Lett. B 417 (1998) 217)

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.....

First calculation based on calculated change in structure in-medium within QMC model – early 90s

RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 46, NUMBER 6 DECEMBER 1992

Towards a microscopic understanding of nuclear structure functions

K. Saito
Physics Division, Tohoku College of Pharmacy, Sendai 981, Japan

A. Michels
Department of Theoretical Physics, Oxford University, 1 Keble Road, Oxford, United Kingdom

A. W. Thomas
Department of Physics and Mathematical Physics, University of Adelaide, P. O. Box 498, Adelaide, South Australia 5001, Australia
(Received 10 February 1992)

More recently by Bentz, Cloët and Thomas using NJL rather than MIT bag model

EMC Effect for Finite Nuclei

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

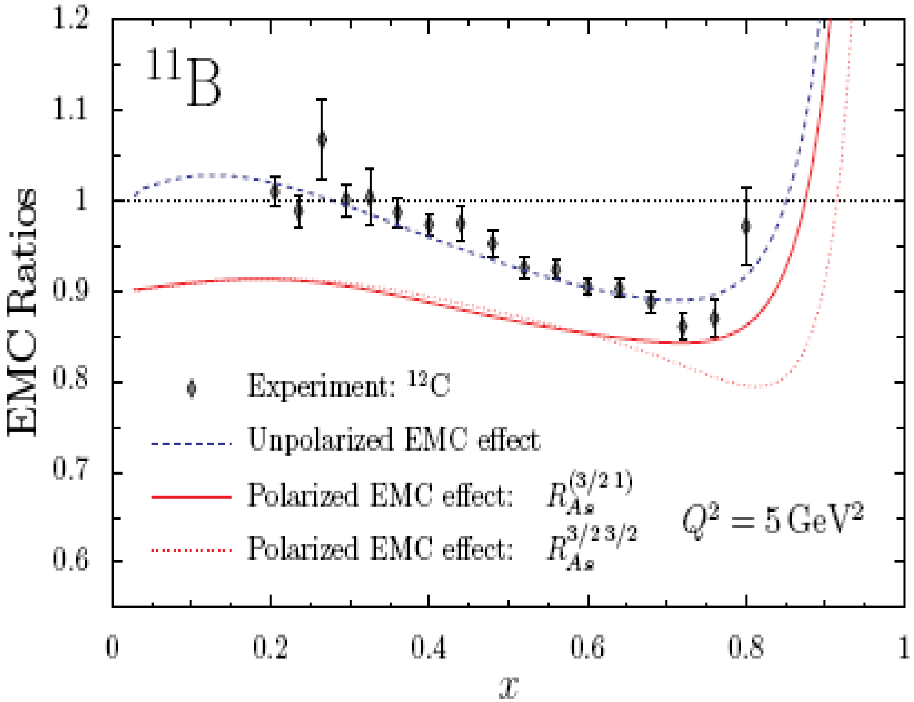


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

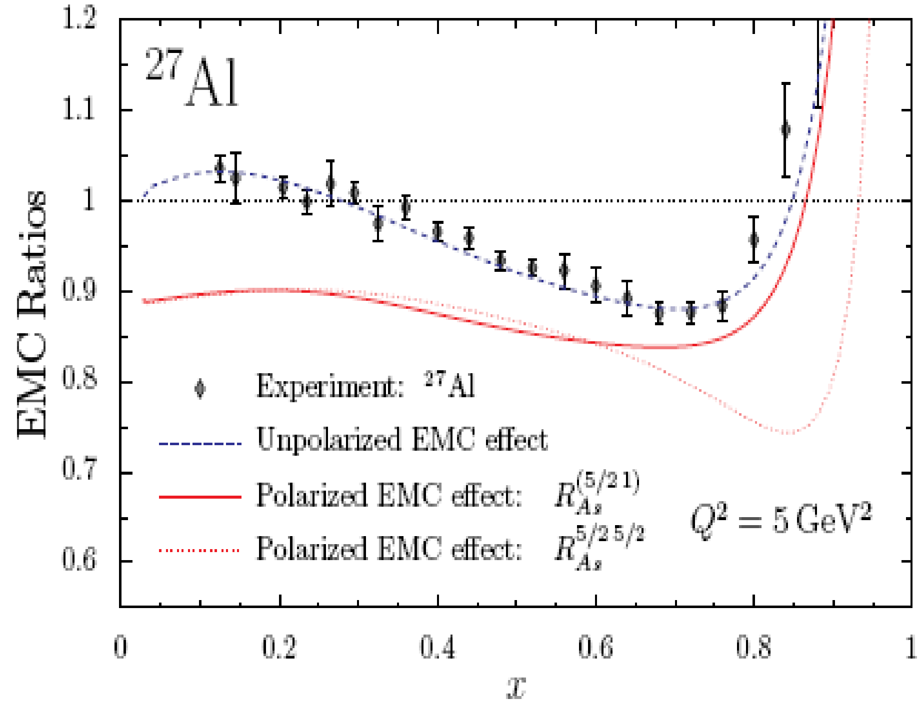


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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

DARK MATTER
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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)

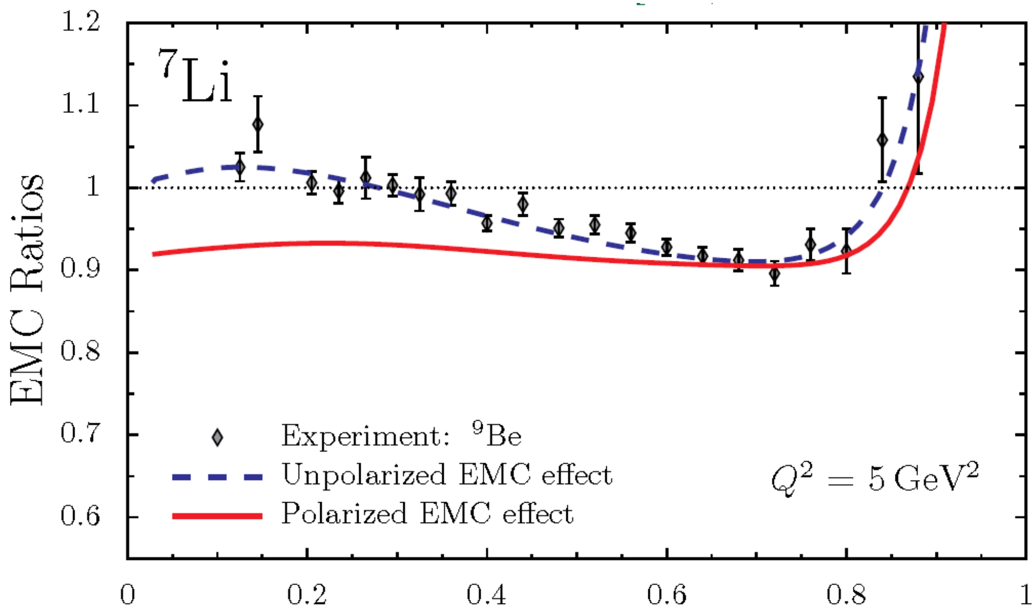
- Nucleons in SRC are depolarized – simple Clebsch-Gordan coefficients - and cannot contribute to spin-EMC effect

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

AWT - Int J Mod Phys 27 (2018) 1840001 (Ernest Henley Memorial)

Approved JLab Experiment

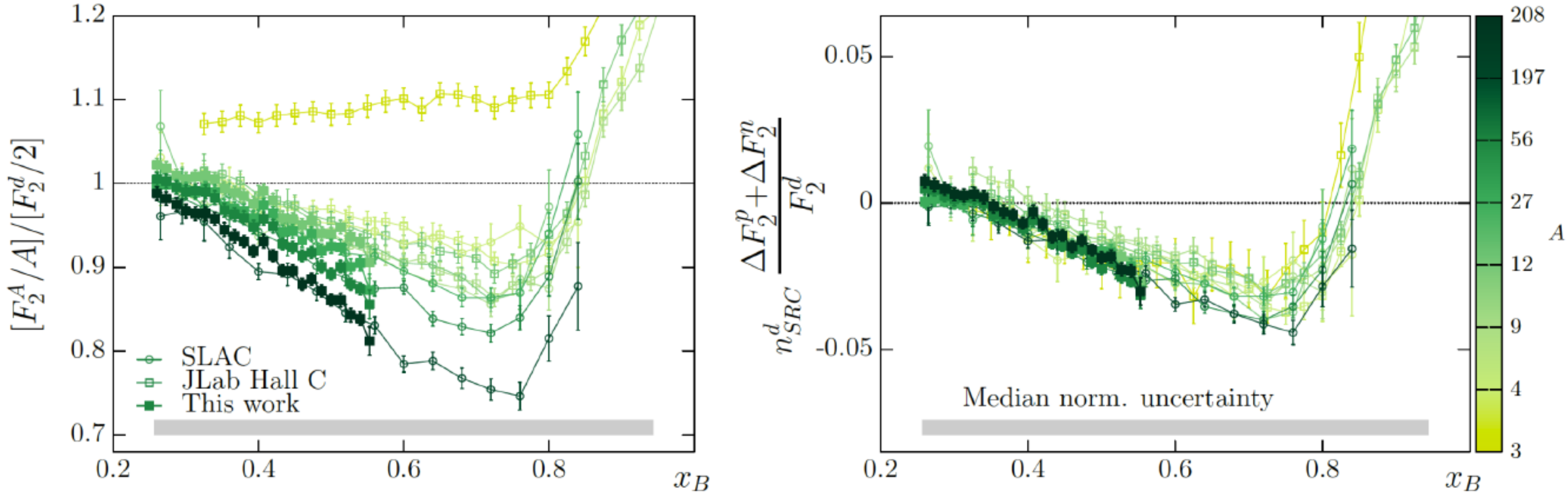
- Effect in ^{7}Li is slightly suppressed because it is a light nucleus and proton does not carry all the spin (simple WF: $P_p = 13/15$ & $P_n = 2/15$)
- Experiment now approved at JLab [E12-14-001] to measure spin structure functions of ^{7}Li (GFMC: $P_p = 0.86$ & $P_n = 0.04$)
- *Everyone with their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

Linear relation of # in SRC vs Slope of EMC effect ➡ SRC explain the EMC effect

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



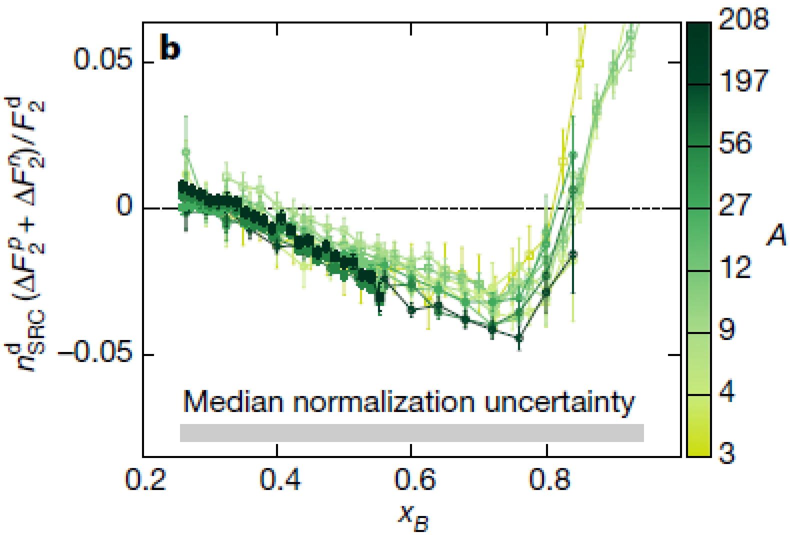
$$F_2^A = (Z - n_{SRC}^A)F_2^p + (N - n_{SRC}^A)F_2^n + n_{SRC}^A(F_2^{p*} + F_2^{n*})$$
$$= ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n),$$

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

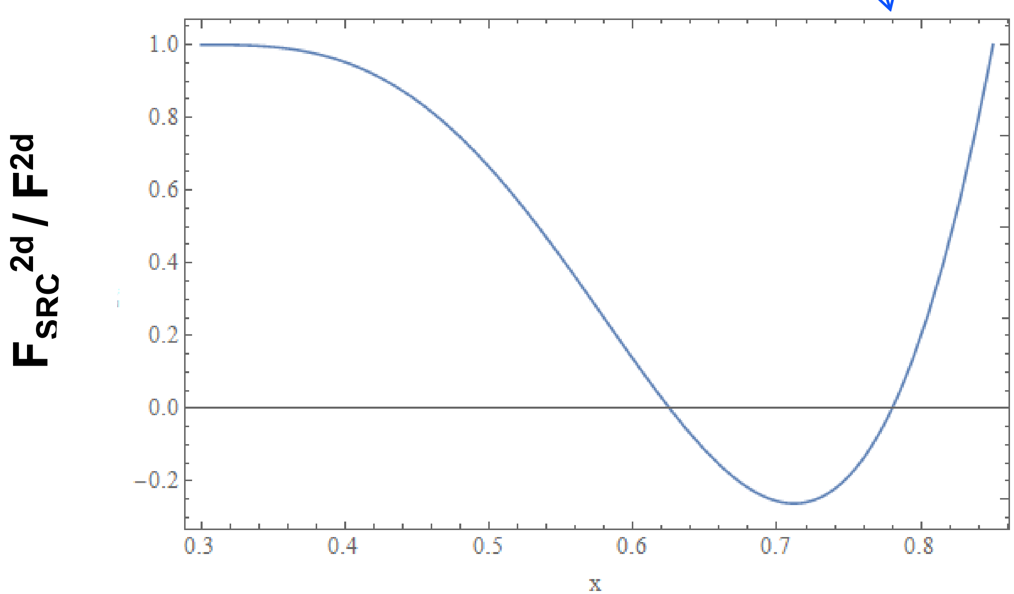
From Doug Higinbotham

My comment

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 greater than or of order 100% in the valence region

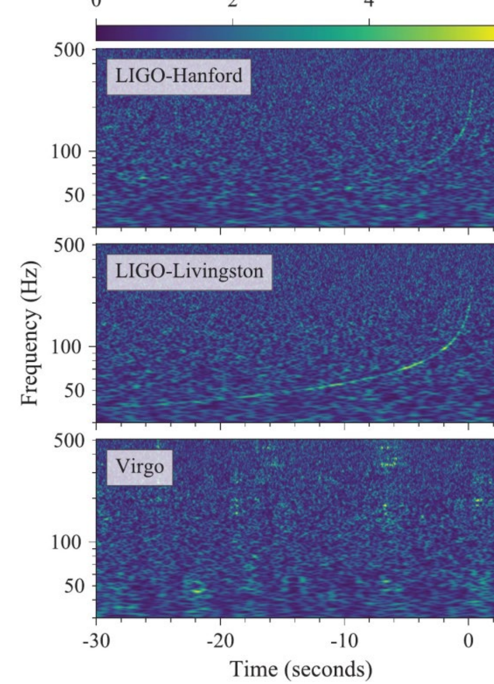


Such a dramatic change is not viable

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

Neutron Stars

LIGO



GW170817: Measurements of neutron star radii and equation of state

The LIGO Scientific Collaboration and The Virgo Collaboration

(compiled 30 May 2018)

On August 17, 2017, the LIGO and Virgo observatories made the first direct detection of gravitational waves from the coalescence of a neutron star binary system. The detection of this gravitational wave signal, GW170817, offers a novel opportunity to directly probe the properties of matter at the extreme conditions found in the interior of these stars. The initial, minimal-assumption analysis of the LIGO and

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DARK MATTER

arXiv:1805.11581

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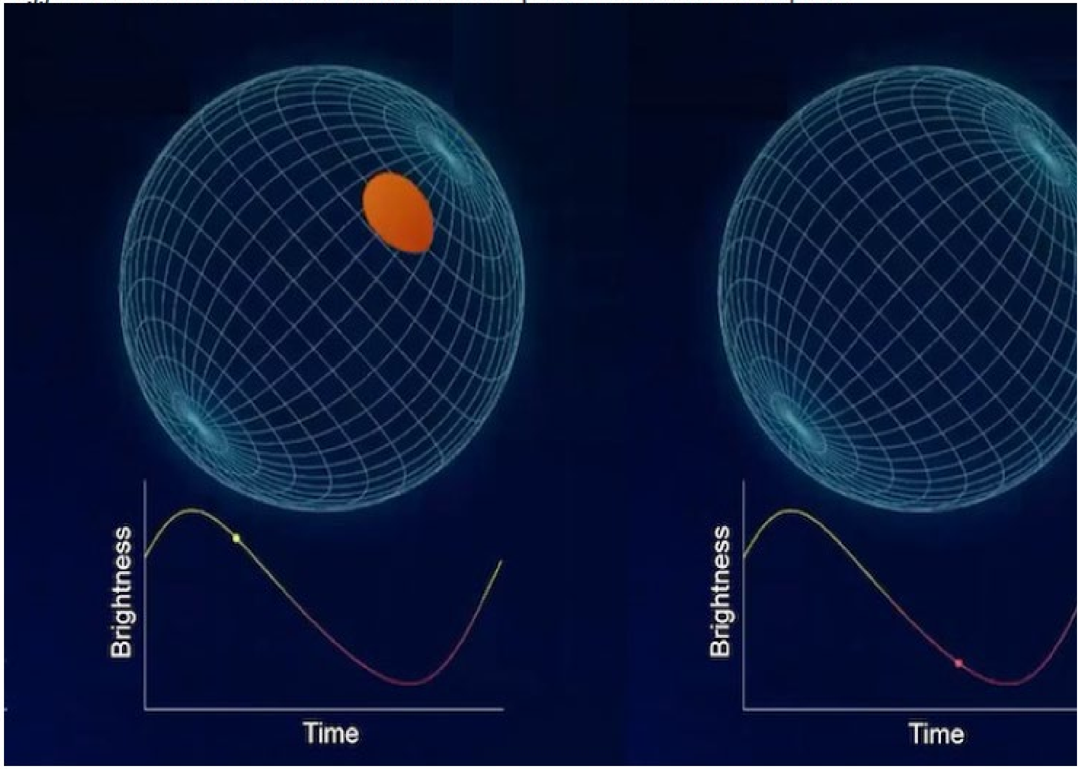
Neutron Star Interior Composition Explorer

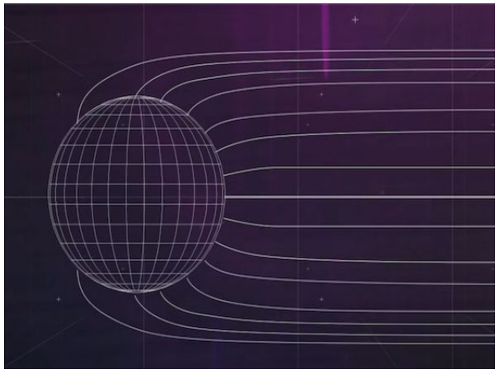
Sizing Up the Most Massive Neutron Star

April 29, 2021• *Physics* 14, 64

A satellite experiment has revealed that the heaviest known neutron star is unexpectedly large, which suggests that the matter in the star's inner core is less "squeezable" than some models predict.

NICER 2021





Goddard Space Flight Center

NICER measures the size of a neutron star by tracking the x-ray emission from "hot spots" on the surface as the star rotates. These spots occur at the magnetic poles of the star, where the field slams particles onto the star surface.

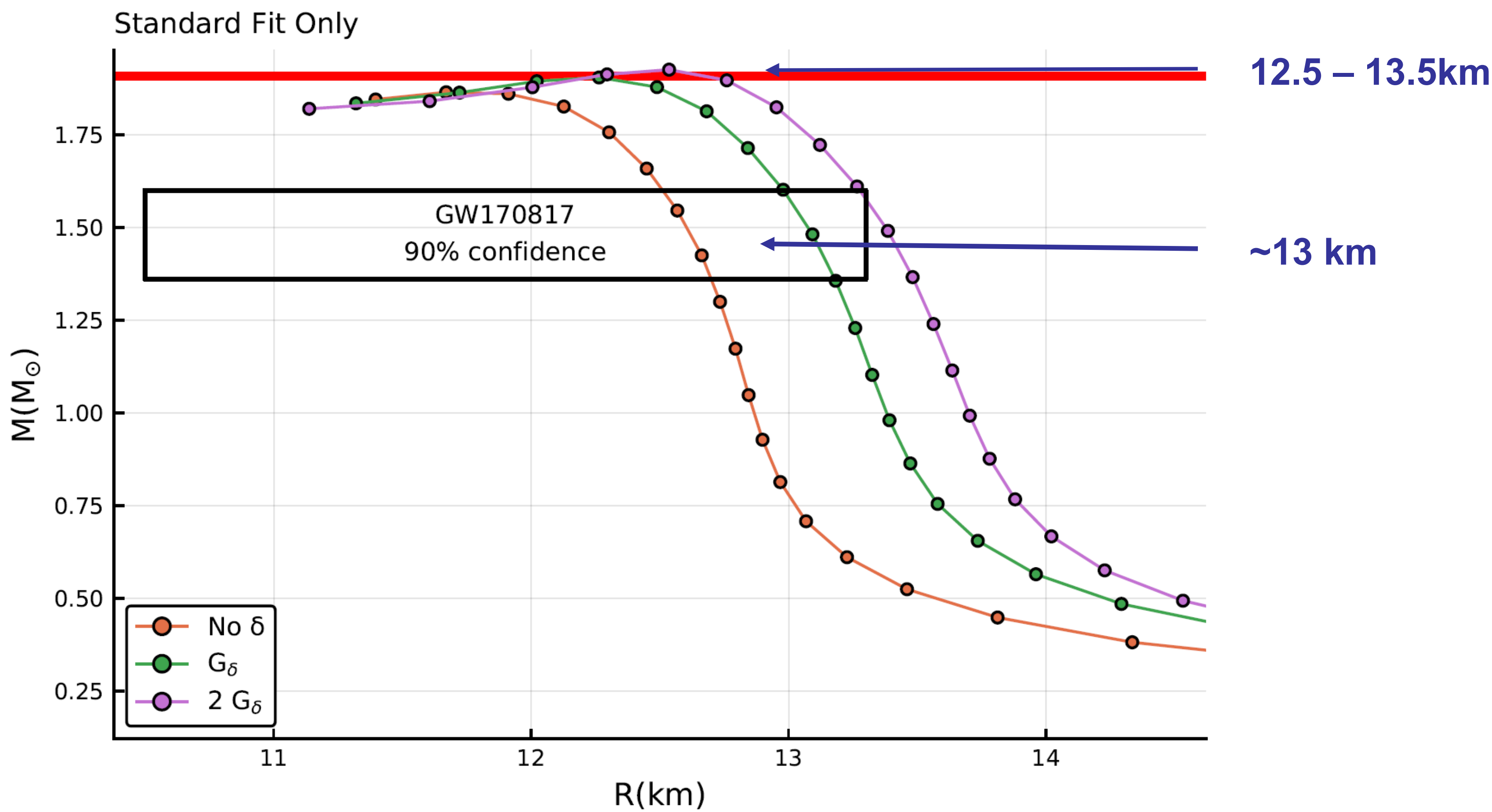
PSR J0030: 1.4 solar masses R ~13km

PSR J0740: ~2.1 solar masses R~12.5 to 13.5km

Recent Study Motivated by GW170817

- **Includes isovector scalar meson**

Nicer Constraint



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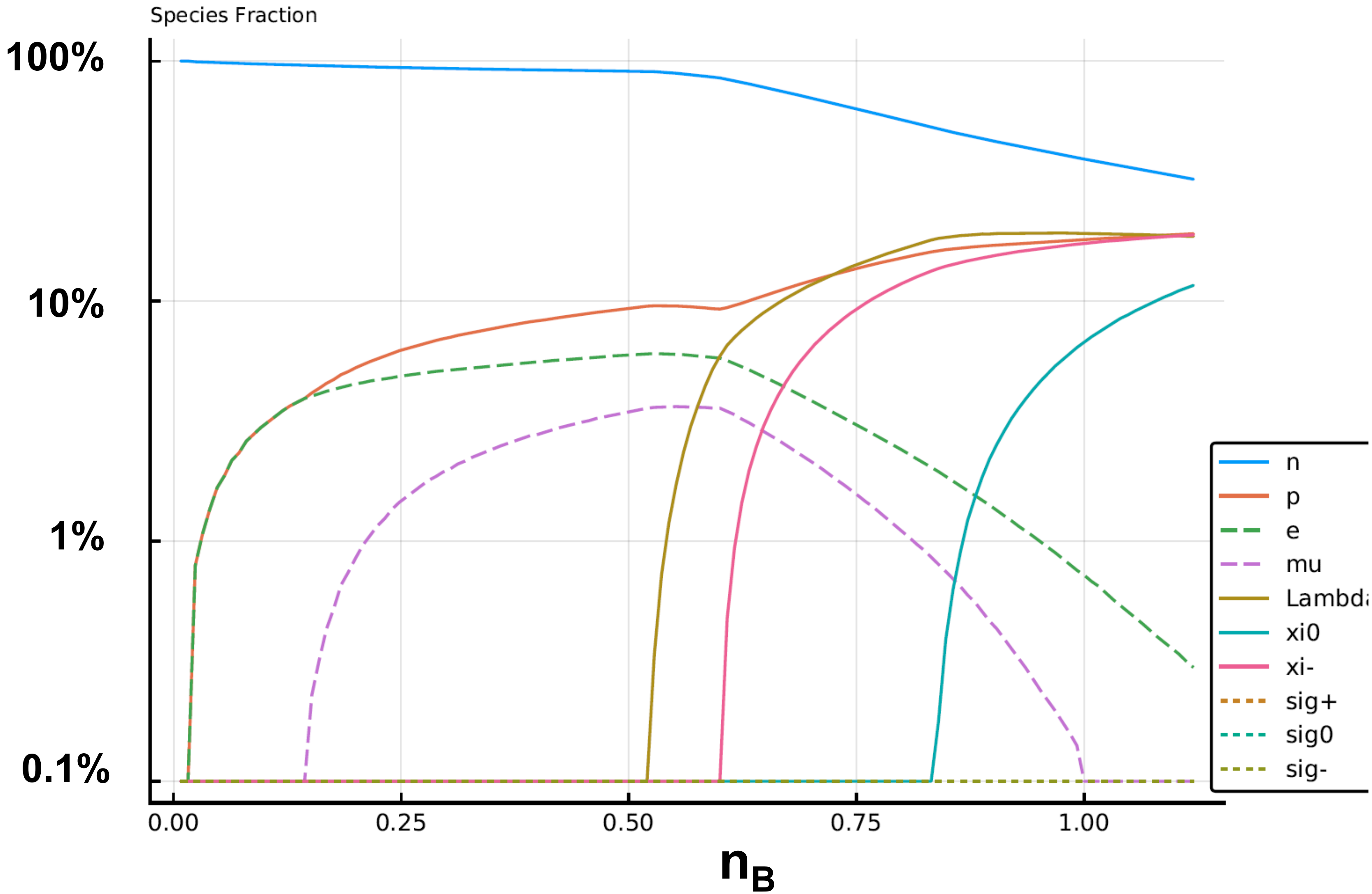
DARK MATTER

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Species Fractions: in β-equilibrium



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DARK MATTER PARTICLE PHYSICS

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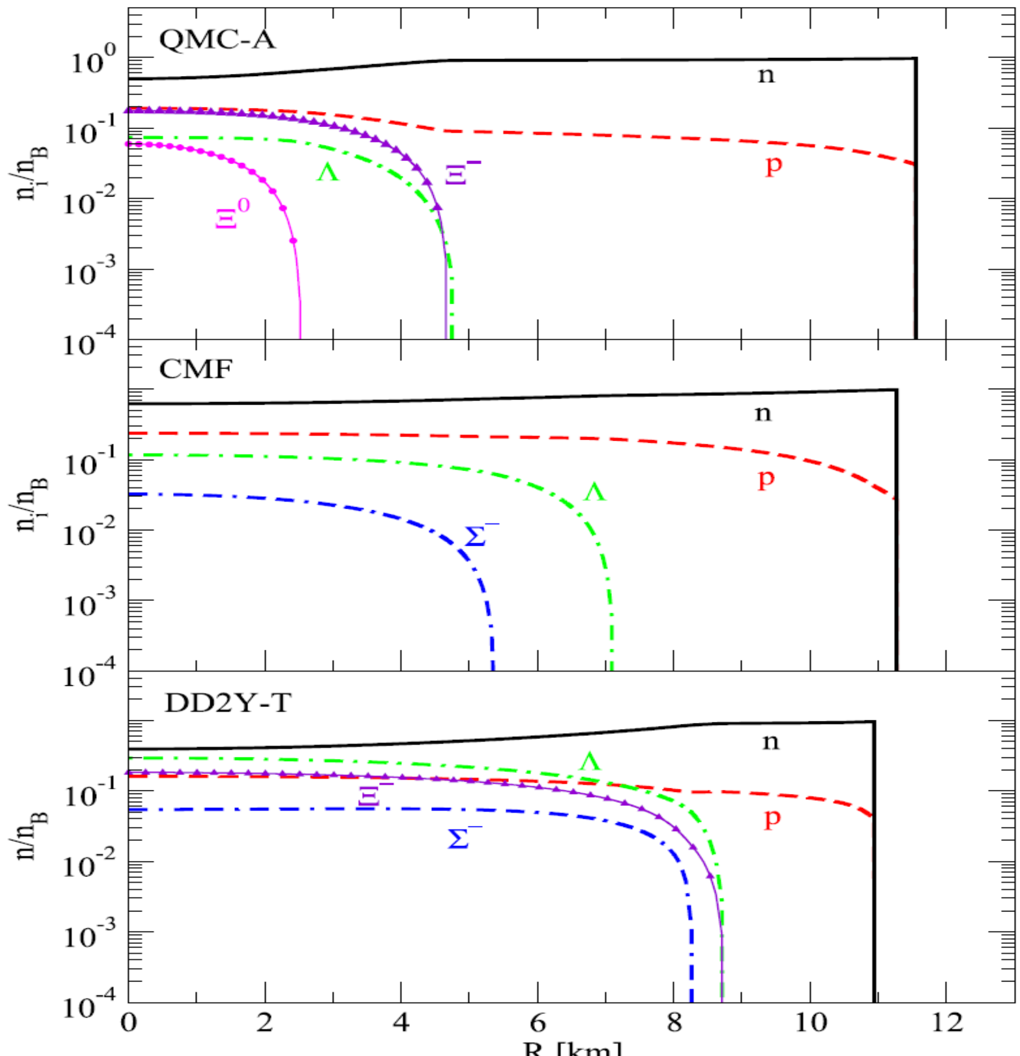
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **502,** 3476–3490 (2021)
Advance Access publication 2021 January 4

doi:10.1093/mnras/staa4006

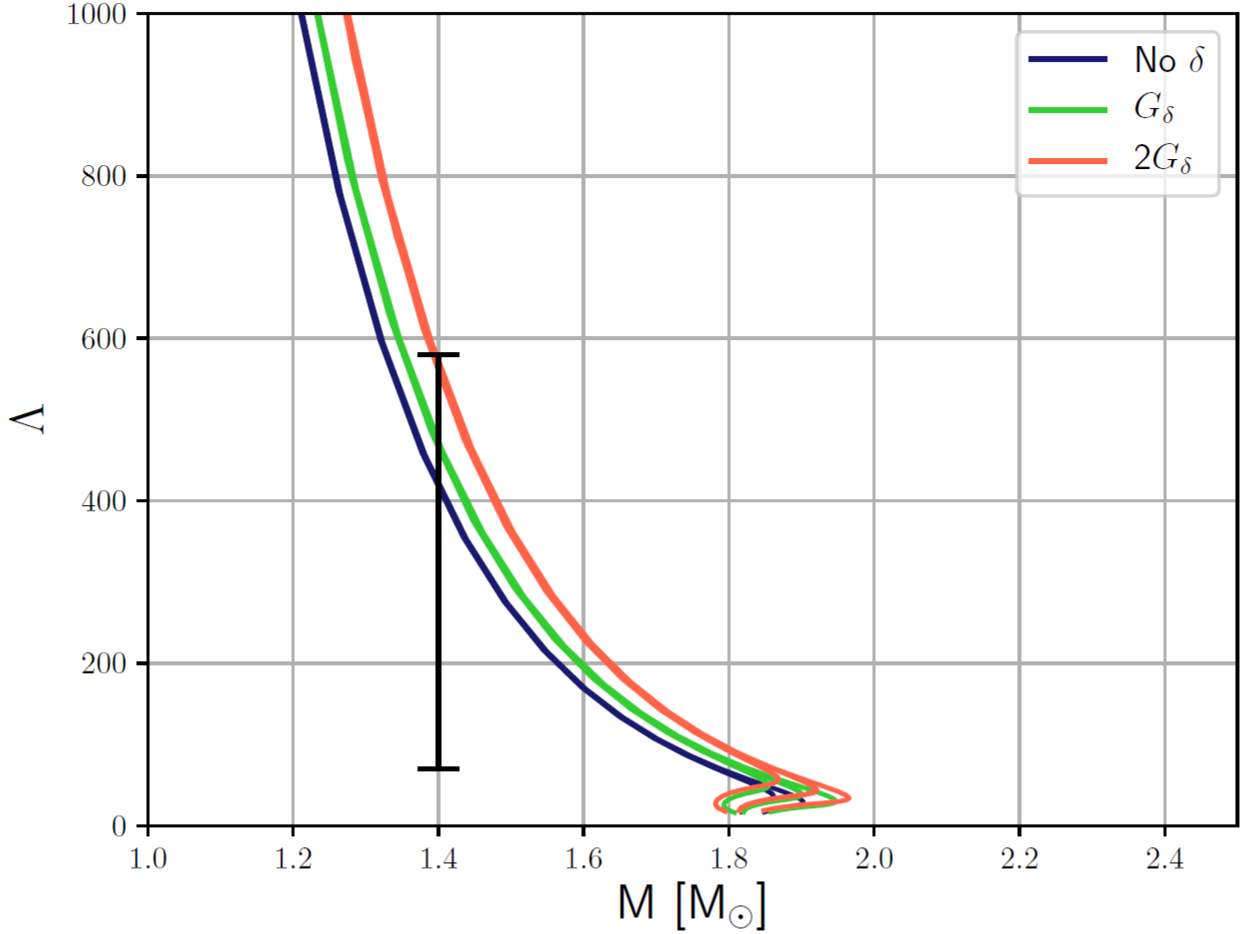
Equation of state of hot dense hyperonic matter in the Quark–Meson-Coupling (QMC-A) model

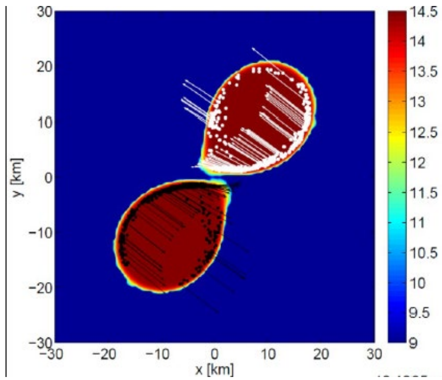
J. R. Stone,[1,2★] V. Dexheimer,[3★] P. A. M. Guichon,[4★] A. W. Thomas[5] and S. Typel[6]



Tidal deformability

- **Band deduced by LIGO-Virgo analysis of GW170817**





$$Q_{ij} = -\lambda(M)\, E_{ij}$$

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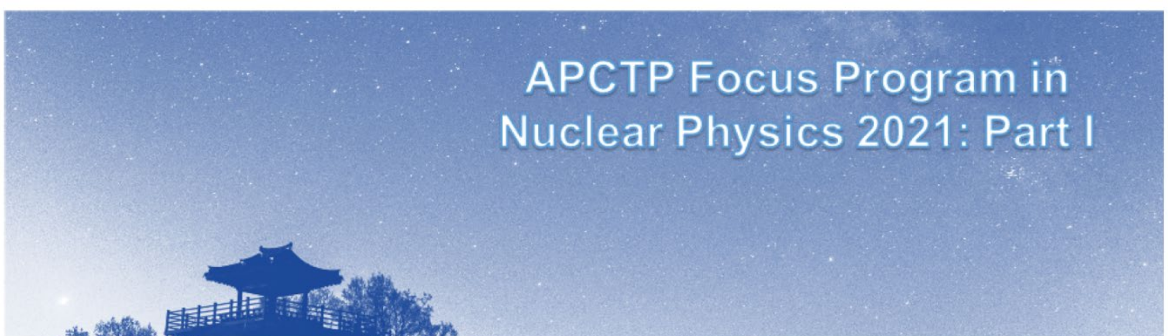
Outlook

- **The study of Hadrons, Nuclei and Neutron Stars is crucial to understanding QCD**

- **It seems natural that the structure of bound systems will be modified in a strongly interacting medium**

- **Theoretical and experimental efforts to identify such changes are vitally important**

- **Amongst other benefits these efforts promise a much deeper and more satisfying understanding of nuclear structure**



APCTP Focus Program in Nuclear Physics 2021 Part I: Hadron properties in a nuclear medium from the quark and gluon degrees of freedom

Special Mentions……

Guichon

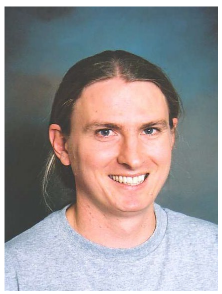
Tsushima

Saito

Stone

Krein

Matevosyan



Cloët

Whittenbury

Simenel

Bentz

Martinez

Motta

Antic

Kalaitzis

Wang

Key papers on QMC

- Two major, recent papers:
  1. Guichon, Matevosyan, Sandulescu, Thomas, Nucl. Phys. A772 (2006) 1.
  2. Guichon and Thomas, Phys. Rev. Lett. 93 (2004) 132502

- Built on earlier work on QMC: e.g.
  3. Guichon, Phys. Lett. B200 (1988) 235
  4. Guichon, Saito, Rodionov, Thomas, Nucl. Phys. A601 (1996) 349

- Major review of applications of QMC to many nuclear systems:
  5. Saito, Tsushima, Thomas, Prog. Part. Nucl. Phys. 58 (2007) 1-167 (hep-ph/0506314)

References to: Covariant Version of QMC

- Basic Model: (Covariant, chiral, confining version of NJL)

- Bentz & Thomas, Nucl. Phys. A696 (2001) 138

- Bentz, Horikawa, Ishii, Thomas, Nucl. Phys. A720 (2003) 95

- Applications to DIS:

- Cloet, Bentz, Thomas, Phys. Rev. Lett. 95 (2005) 052302

- Cloet, Bentz, Thomas, Phys. Lett. B642 (2006) 210

- Applications to neutron stars – including SQM:

- Lawley, Bentz, Thomas, Phys. Lett. B632 (2006) 495

- Lawley, Bentz, Thomas, J. Phys. G32 (2006) 667