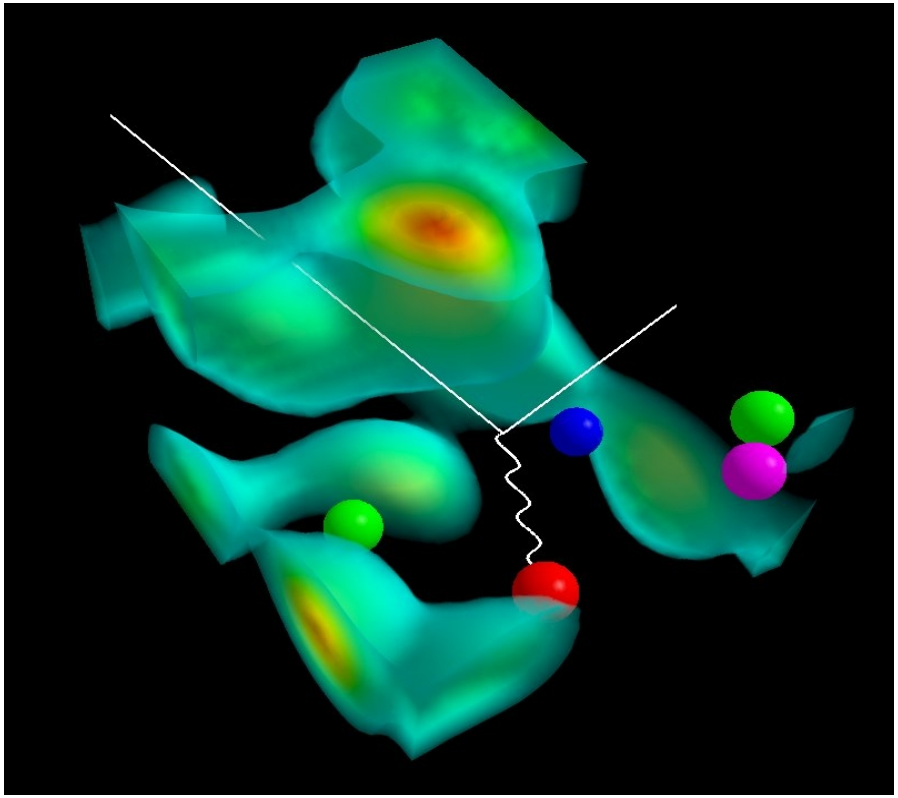
Fundamental Nuclear Physics: From Quarks and Gluons to Finite Nuclei and Neutron Stars



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ARC Centre of Excellence for Particle Physics at the Terascale

Anthony W. Thomas

International School of Nuclear Physics : 40th Course
Erice : 17th September 2018

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SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Outline

I. Nuclei from Quarks
  − start from a QCD-inspired model of *hadron* structure
  − develop a quantitative theory of nuclear structure

II. Search for observable effects of the change in hadron structure in-medium

III. Neutron Stars

IV. Dark Matter:
  − proposed explanation for neutron lifetime anomaly

I. Insights into nuclear structure

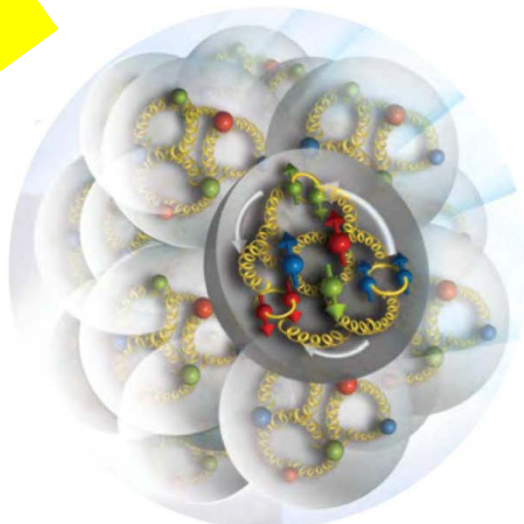
− what is the atomic nucleus?

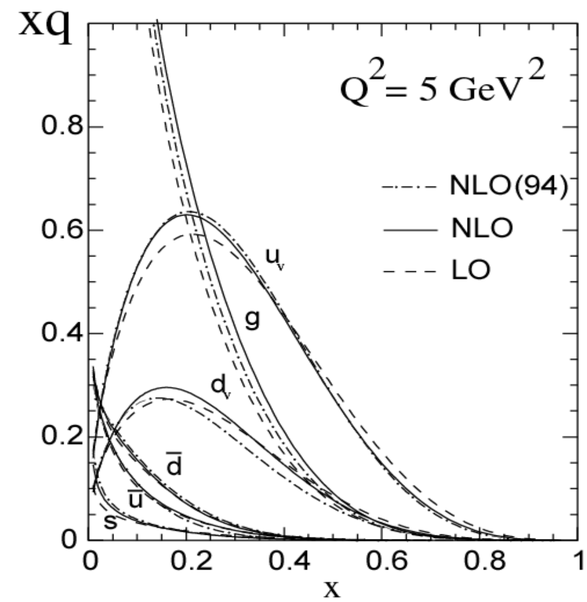
There are two very different extremes….

A. Nuclear Femtography

Science of mapping the position and motion of quarks and gluons in the nucleus.

Artist's Conception of Quark and Gluons **in a proton and nucleus**





12 GeV

REQUIRES:

- *High beam polarization*
- *High electron current*
- *High target polarization*
- *Large solid angle spectrometers*

.. is just beginning

From Rolf Ent EINN2017

B. Extreme Chiral Effective Field Theory

- **"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"**

- anonymous referee 2017

TRUE OR  **?**

- **Actually not so modern……**

D. Alan Bromley (Yale) to Stan Brodsky in 1982

"Stan, you have to understand -- in nuclear physics we are only interested in how protons and neutrons make up a nucleus.

We are not interested in what is inside of a proton."

Like this beautiful scene – very relaxing

D. Alan Bromley (Yale) to Stan Brodsky in 1982

"Stan, you have to understand -- in nuclear physics we are only interested in how protons and neutrons make up a nucleus.

We are <u>not</u> interested in what is inside of a proton."

Moral: A comfortable picture is not necessarily the right one.....

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What do we know?

- Since 1970s, intermediate range NN attraction is strong Lorentz scalar
- In relativistic treatments (RHF, RBHF, QHD…) this leads to mean scalar field ~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

Suggests a different approach : QMC Model

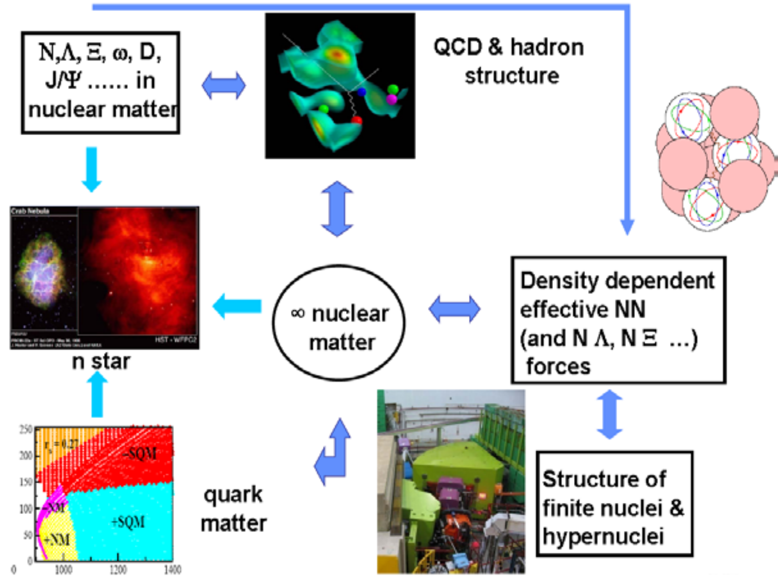
(Guichon, Saito, Tsushima et al., Rodionov et al.
- see Saito et al., Prog. Part. Nucl .Phys. 58 (2007) 1 and
Prog. Part. Nucl. Phys. 100 (2018) 262-297 for reviews)

- **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 <u>only 3 parameters</u>** (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 <u>self-consistently</u> for the internal structure of baryons in-medium**

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Self-consistent solution of 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 <u>EFFICIENT BECAUSE QUARKS ARE ALMOST MASSLESS</u>)

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

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Effect of scalar field on quark spinor

- **MIT bag model: quark spinor modified in bound nucleon**

$$\Psi = \frac{\mathcal{N}}{4\pi}\begin{pmatrix} j_0(xu'/R_B) \\ i\beta_q\vec{\sigma}\cdot\hat{u}' j_1(xu'/R_B) \end{pmatrix}\chi_m$$

- **Lower component enhanced by attractive scalar field**

$$\beta_q = \sqrt{\frac{\Omega_0 - m_q^* R_B}{\Omega_0 + m_q^* R_B}}$$

- **This leads to a *very small* (~1% at ρ_0) *increase in bag radius***

- **It also *suppresses the scalar coupling to the nucleon as the scalar field increases***

$$\frac{\Omega_0/2 + m_q^* R_B(\Omega_0 - 1)}{\Omega_0(\Omega_0 - 1) + m_q^* R_B/2} = \int \bar{\psi}\,\psi\ dV$$

- **This is the "scalar polarizability": a new saturation mechanism for nuclear matter**

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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

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

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

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

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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:**

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

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Derivation of effective Force (cont.)

$$\mathcal{H}_0 + \mathcal{H}_3 = \rho^2\left[\frac{-3G_\rho}{32} + \boxed{\frac{G_\sigma}{8(1+d\rho G_\sigma)^3}} - \frac{G_\sigma}{2(1+d\rho G_\sigma)} + \frac{3G_\omega}{8}\right] + (\rho_n - \rho_p)^2\left[\frac{5G_\rho}{32} + \boxed{\frac{G_\sigma}{8(1+d\rho G_\sigma)^3}} - \frac{G_\omega}{8}\right],$$

$$\mathcal{H}_{\text{eff}} = \left[\left(\frac{G_\rho}{8m_\rho{}^2} - \frac{G_\sigma}{2m_\sigma{}^2} + \frac{G_\omega}{2m_\omega{}^2} + \frac{G_\sigma}{4M_N{}^2}\right)\rho_n + \left(\frac{G_\rho}{4m_\rho^2} + \frac{G_\sigma}{2M_N^2}\right)\rho_p\right]\tau_n + p \leftrightarrow n,$$

$$\mathcal{H}_{\text{fin}} = \left[\left(\frac{3G_\rho}{32m_\rho{}^2} - \frac{3G_\sigma}{8m_\sigma{}^2} + \frac{3G_\omega}{8m_\omega{}^2} - \frac{G_\sigma}{8M_N{}^2}\right)\rho_n + \left(\frac{-3G_\rho}{16m_\rho{}^2} - \frac{G_\sigma}{2m_\sigma{}^2} + \frac{G_\omega}{2m_\omega{}^2} - \frac{G_\sigma}{4M_N{}^2}\right)\rho_p\right]\nabla^2(\rho_n) + p \leftrightarrow n,$$

$$\mathcal{H}_{\text{so}} = \nabla \cdot J_n\left[\left(\frac{-3G_\sigma}{8M_N{}^2} - \frac{3G_\omega(-1+2\mu_s)}{8M_N{}^2} - \frac{3G_\rho(-1+2\mu_v)}{32M_N{}^2}\right)\rho_n + \left(\frac{-G_\sigma}{4M_N{}^2} + \frac{G_\omega(1-2\mu_s)}{4M_N{}^2}\right)\rho_p\right] + p \leftrightarrow n.$$

Spin-orbit force predicted!

Note the totally new, subtle density dependence

Systematic approach to finite nuclei

J.R. Stone, P.A.M. Guichon, P. G. Reinhard & A.W. Thomas:
(Phys Rev Lett, 116 (2016) 092501)

- **Constrain 3 basic quark-meson couplings (g_σ^q, g_ω^q, g_ρ^q) so that nuclear matter properties are reproduced within errors**

$-17 < E/A < -15$ MeV

$0.14 < \rho_0 < 0.18$ fm^{-3}

$28 < S_0 < 34$ MeV

$L > 20$ MeV

$250 < K_0 < 350$ MeV

- **Fix at overall best description of finite nuclei** (+2 pairing pars)

- **Benchmark comparison: SV-min 16 parameters** (11+5 pairing)

Overview of 106 Nuclei Studied – Across Periodic Table

Element	Z	N	Element	Z	N
C	6	6 -16	Pb	82	116 - 132
O	8	4 -20	Pu	94	134 - 154
Ca	20	16 – 32	Fm	100	148 - 156
Ni	28	24 – 50	No	102	152 - 154
Sr	38	36 – 64	Rf	104	152 - 154
Zr	40	44 -64	Sg	106	154 - 156
Sn	50	50 – 86	Hs	108	156 - 158
Sm	62	74 – 98	Ds	110	160
Gd	64	74 -100			

Not fit

N	Z	N	Z
20	10 – 24	64	36 - 58
28	12 – 32	82	46 - 72
40	22 – 40	126	76 - 92
50	28 – 50		

i.e. We look at most challenging cases of p- or n-rich nuclei

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Overview

data	rms error %	
	QMC	SV-min
fit nuclei:		
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

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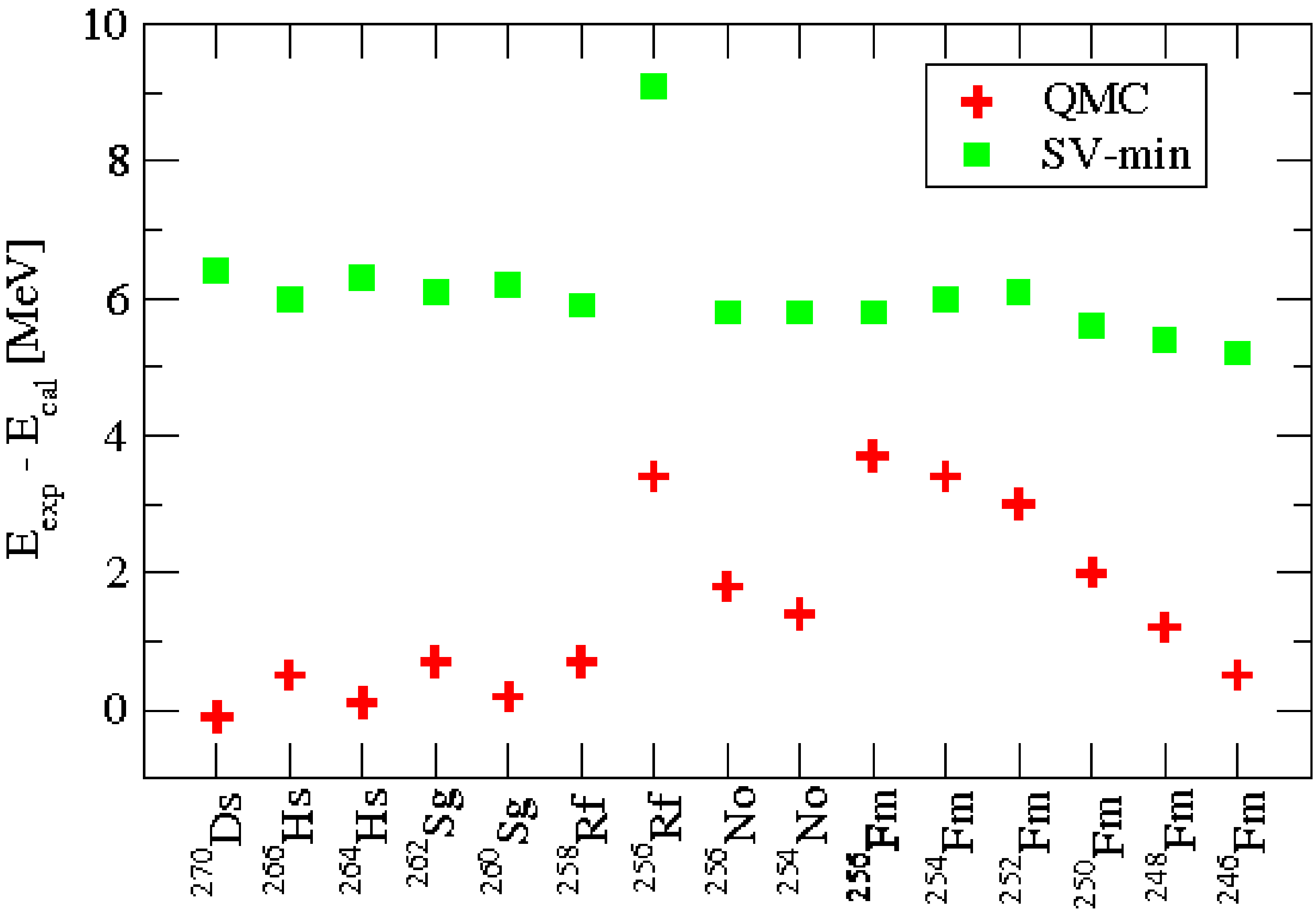
Superheavy Binding : 0.1% accuracy



Stone et al., PRL 116 (2016) 092501

More on Superheavies

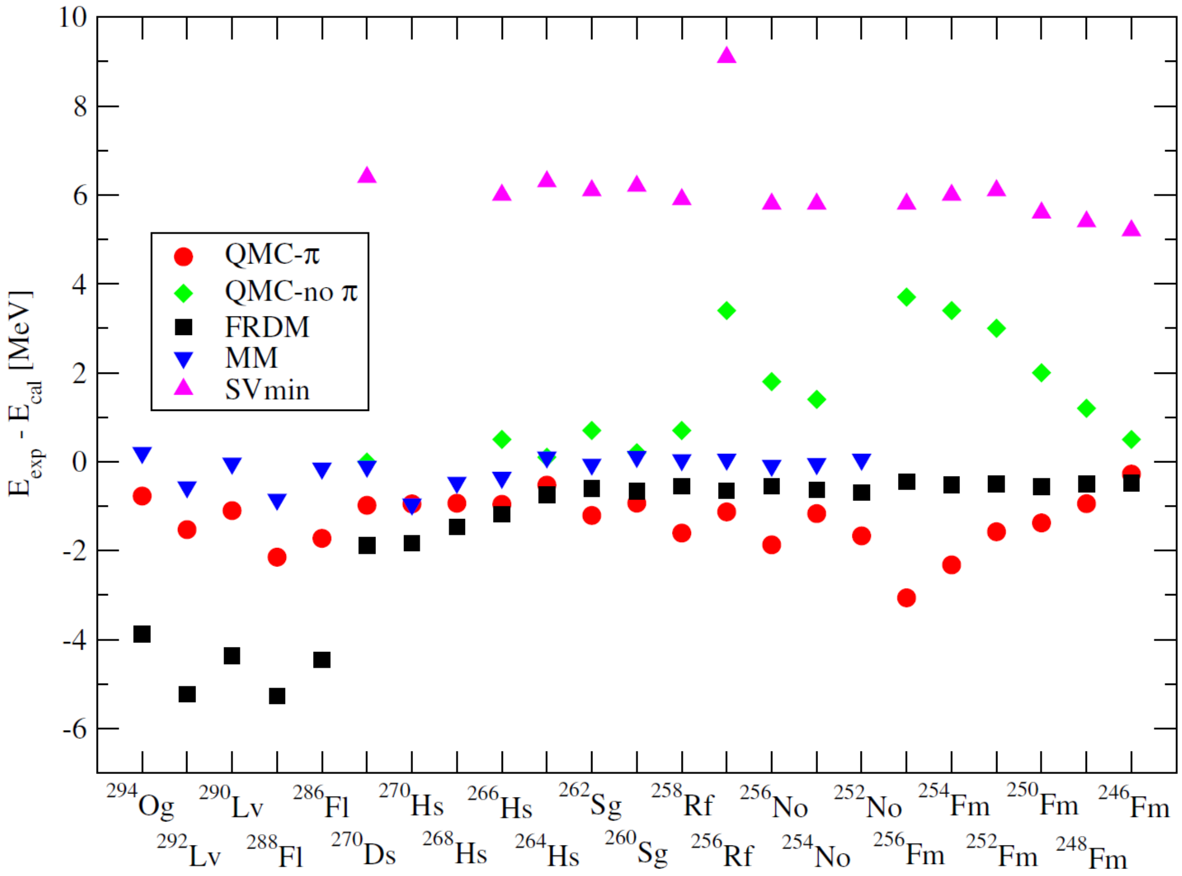
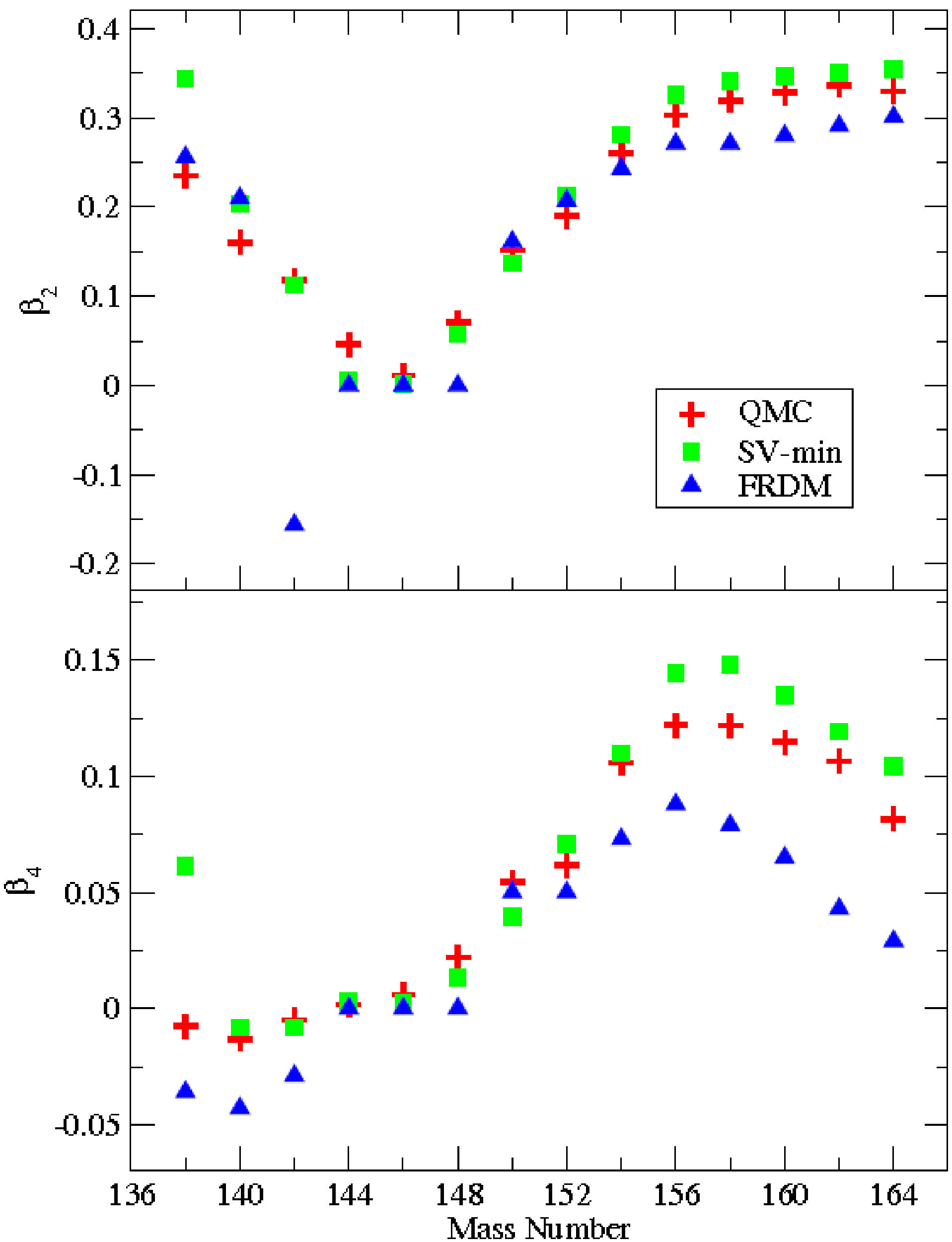


Figure 1. (Color online). Ground state binding energies of selected 'benchmark' even-even superheavy nuclei. The experimental data were taken from [27, 28].

Stone *et al.*, E P J Web of Conferences 163 (2017) 00057

Deformation in Gd (Z=64) Isotopes



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Quadrupole deformation in Superheavies

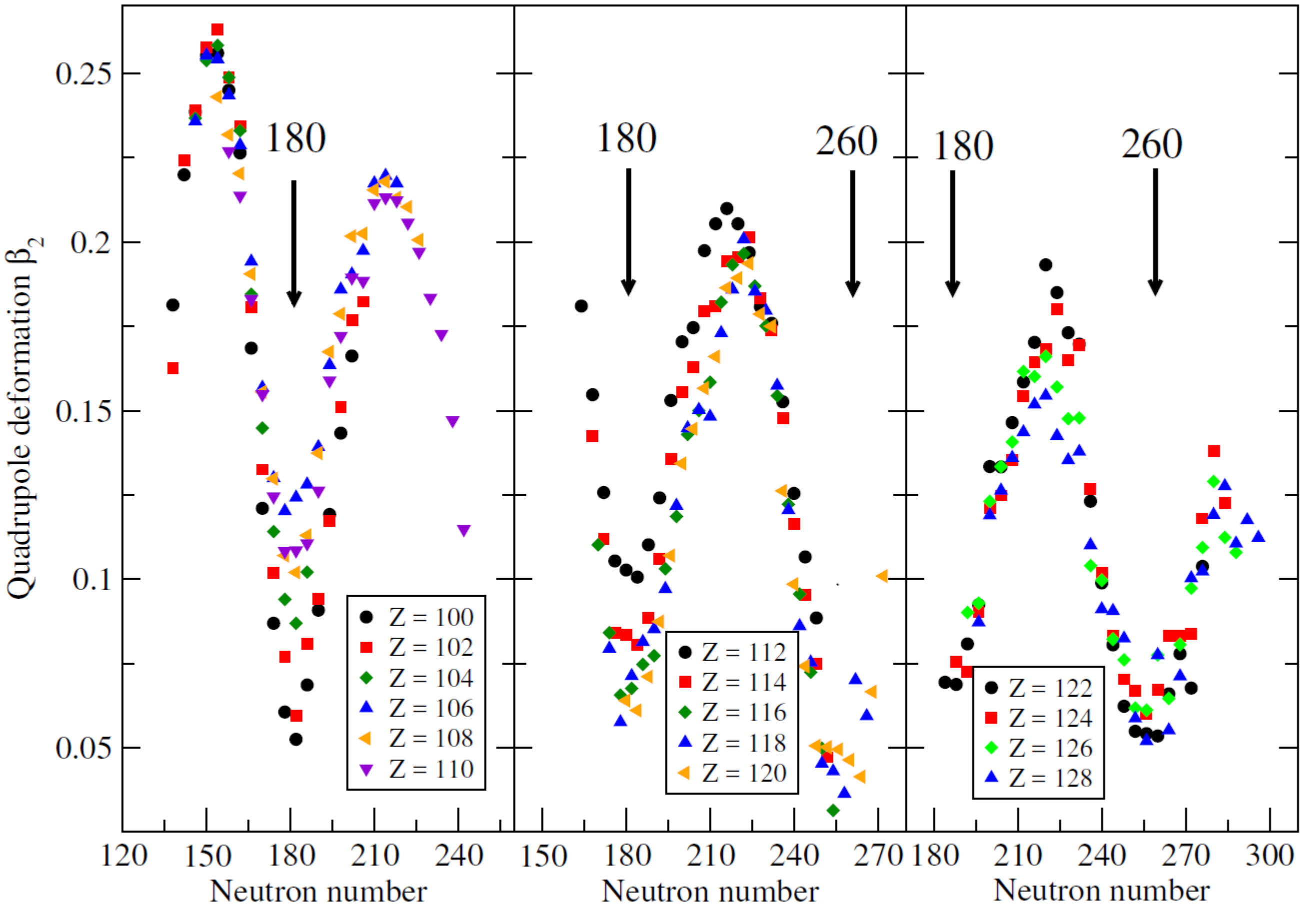

Figure 2. (Color online). Quadrupole deformation calculated in QMCπ for isotopes with proton number $100 < Z < 128$.

Stone *et al.*, E P J Web of Conferences 163 (2017) 00057

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Drip line predictions

Table 1. Neutron numbers corresponding to proton and neutron drip lines, derived from the Fermi energy for isotopes of elements 96 < Z <136

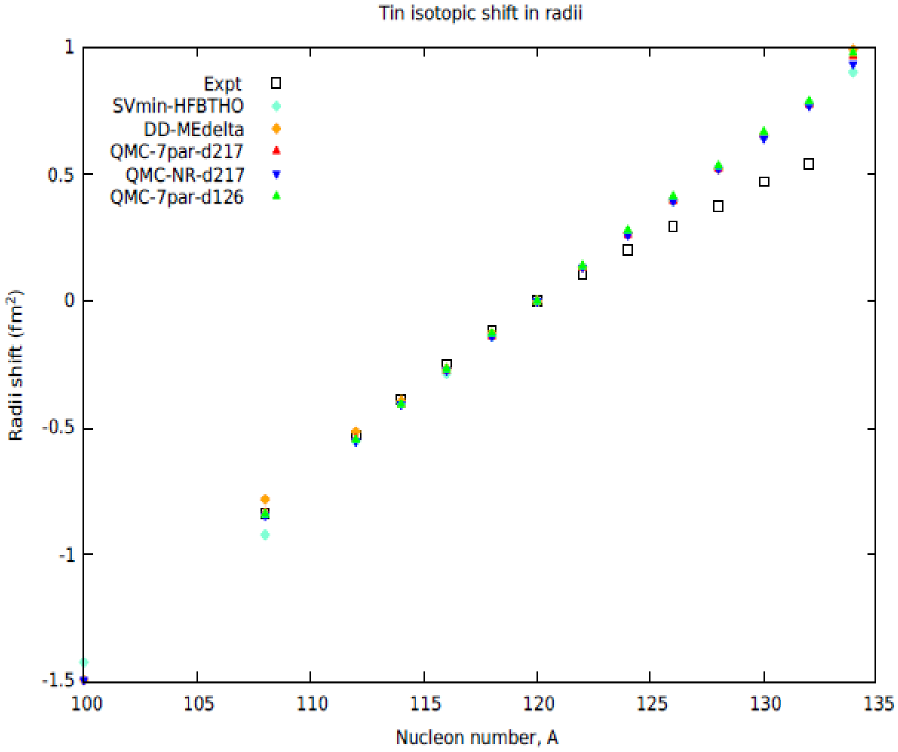
Z	N(p)	N(n)	Z	N(p)	N(n)
96	132	224	118	174	278
98	134	226	120	180	286
100	138	230	122	184	290
102	138	236	124	188	296
104	146	240	126	192	298
106	146	242	128	196	302
108	154	246	130	202	306
110	158	250	132	208	310
112	164	256	134	214	314
114	168	260	136	218	314
116	170	268			

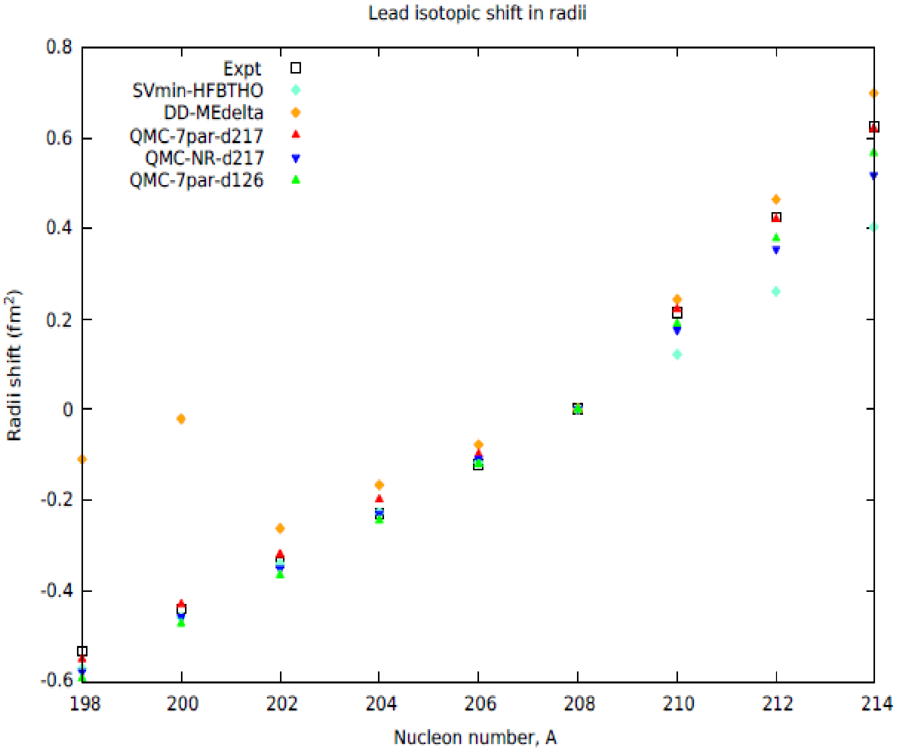
Stone *et al.*, E P J Web of Conferences 163 (2017) 00057

Extended QMC – Martinez, Konieczka, Bąszyk *et al.*

Isotopic Radius Shift

- **Not bad for Tin, excellent for Pb isotopes**





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Summary: Finite Nuclei

- The effective force was *derived* at the quark level *based upon changing structure of bound nucleon*
- Has many less parameters but reproduces nuclear properties at a level comparable with the best phenomenological Skyrme forces
- Looks like standard nuclear force
- BUT underlying theory also predicts modified internal structure and hence modified
  - DIS structure functions
  - elastic form factors......

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Nuclear DIS Structure Functions : The EMC Effect

To address questions like this one MUST start with a theory that quantitatively describes nuclear structure and allows calculation of structure functions

– very, very few examples.....

Theoretical Understanding

- Still numerous proposals but few consistent theories
- Initial studies used MIT bag[1] to estimate effect of self-consistent change of structure in-medium
  − but better to use a covariant theory
- For that Bentz and Thomas[2] re-derived change of nucleon structure in-medium in the NJL model
- This set the framework for sophisticated studies by Bentz, Cloët and collaborators over the last decade

[1] Thomas, Michels, Schreiber and Guichon, Phys. Lett. B233 (1989) 43
[2] Bentz and Thomas, Nucl. Phys. A696 (2001) 138

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EMC Effect for Finite Nuclei

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

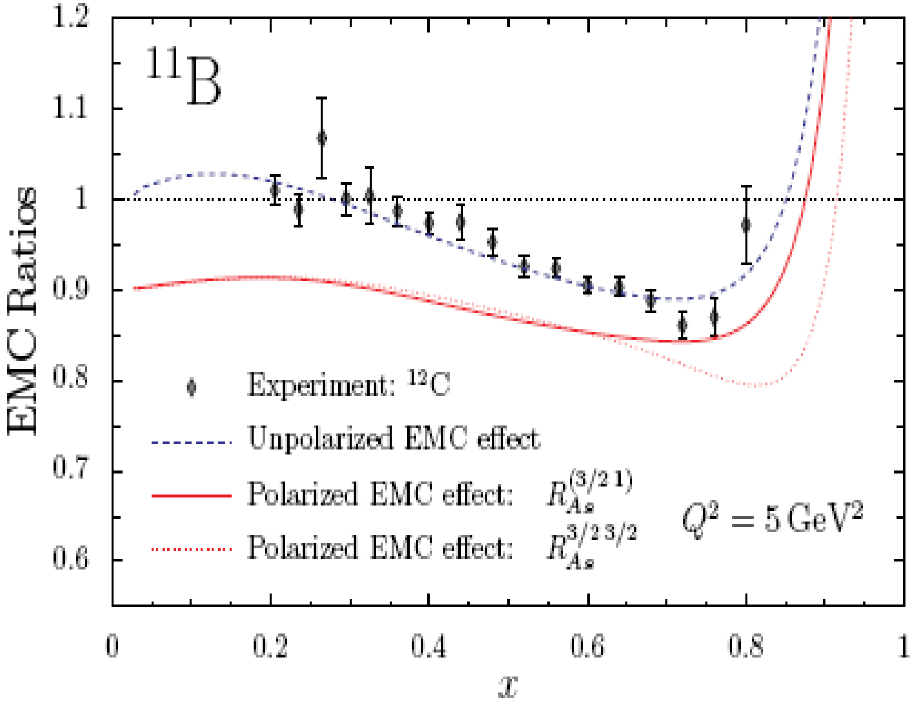


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

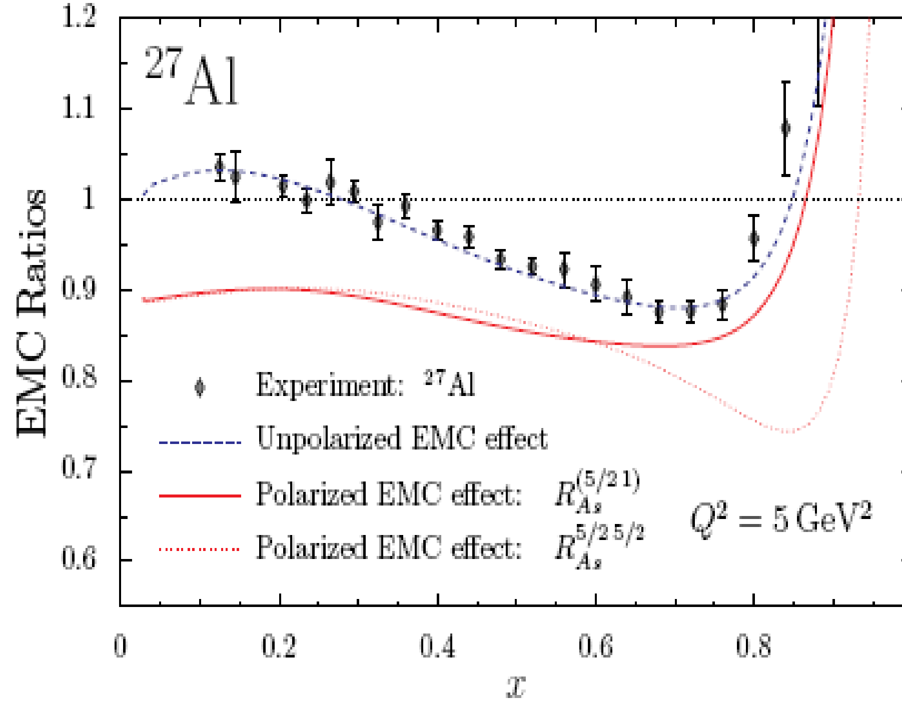
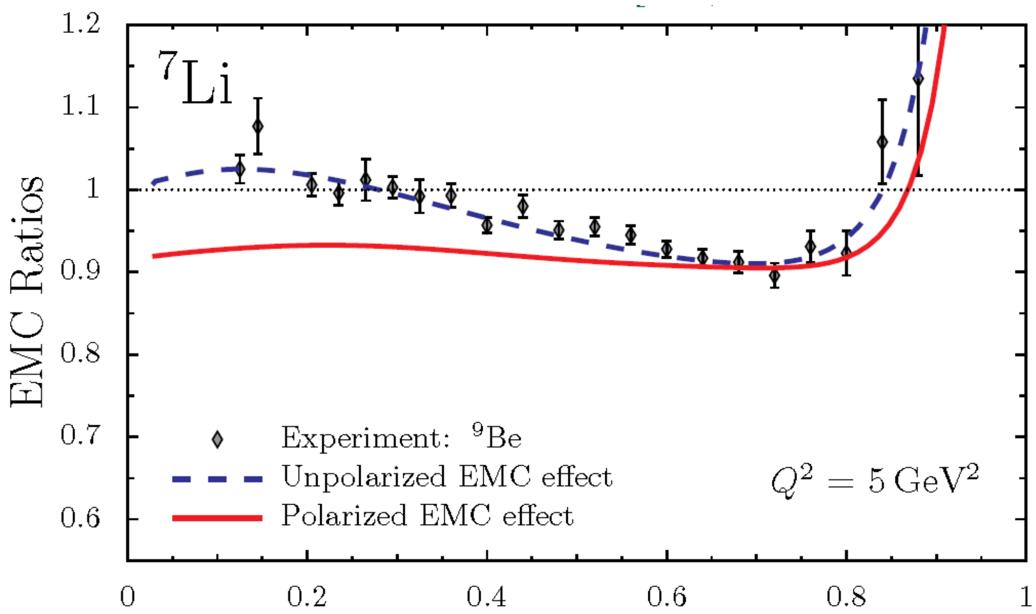


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

Cloët, Bentz &Thomas, Phys. Lett. B642 (2006) 210

Approved JLab Experiment

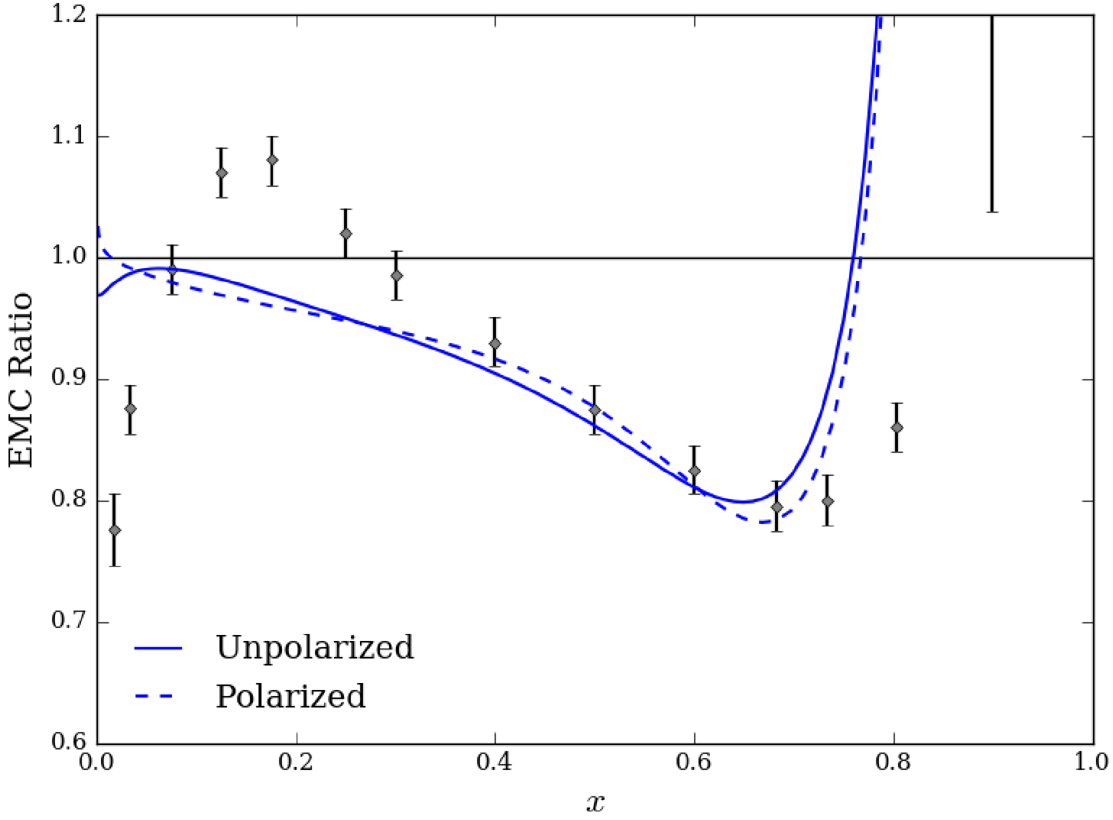
- Effect in ^{7}Li is slightly suppressed because it is a light nucleus and proton does not carry all the spin (simple WF: $P_p = 13/15$ & $P_n = 2/15$)
- Experiment now approved at JLab [E12-14-001] to measure spin structure functions of ^{7}Li (GFMC: $P_p = 0.86$ & $P_n = 0.04$)
- *Everyone with their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

Model dependence of spin-EMC effect

Went back to QMC, with defects of bag model (especially too small at large-x). Simply examine, without details of nuclear structure, at ρ_0, how the polarized EMC effect compares with the unpolarised effect.



S. Tronchin et al. – Phys.Lett. B783 (2018) 247

Isovector EMC Effect

- New realization concerning EMC effect in this approach:
  - isovector force in nucleus (like Fe) with N≠Z effects ALL u and d quarks in the nucleus
  - subtracting structure functions of extra neutrons is not enough
  - *there is a shift of momentum from <u>all</u> u to <u>all</u> d quarks*
- Sign and magnitude of this effect exhibits little model dependence

Cloet *et al*., Phys.Rev.Lett.102:252301,2009
Londergan et al., Phys Rev D67 (2003) 111901

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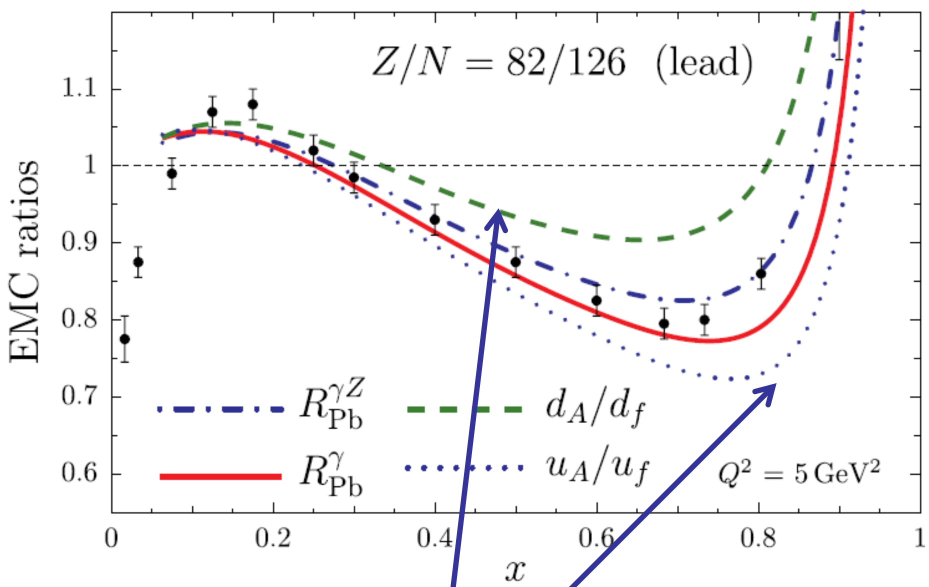
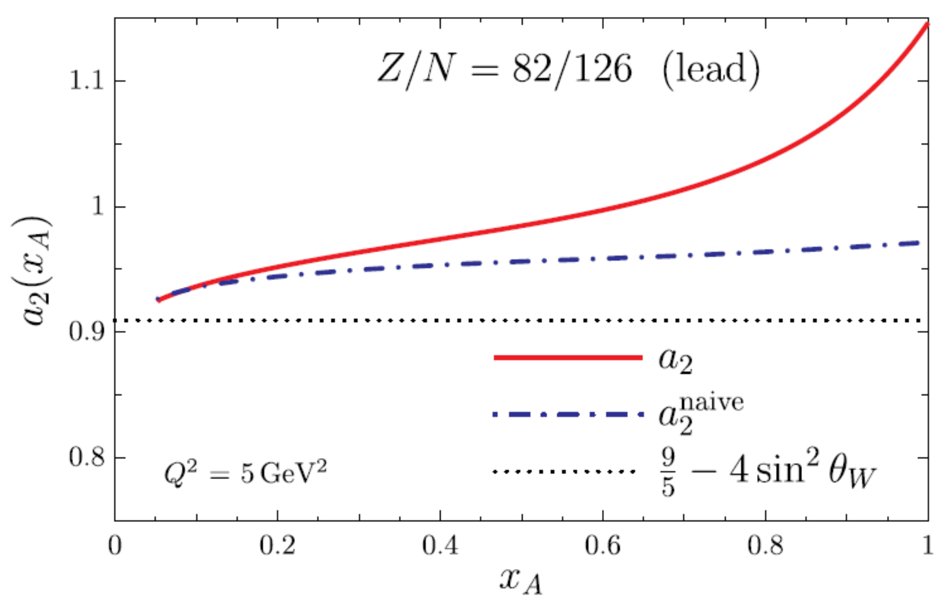
PRL 109, 182301 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

Parity-Violating Deep Inelastic Scattering and the Flavor Dependence of the EMC Effect

I. C. Cloët,[1] W. Bentz,[2] and A. W. Thomas[1]



$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{em}}\left[a_2(x_A) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x_A)\right]$$



Ideally tested at EIC with CC reactions

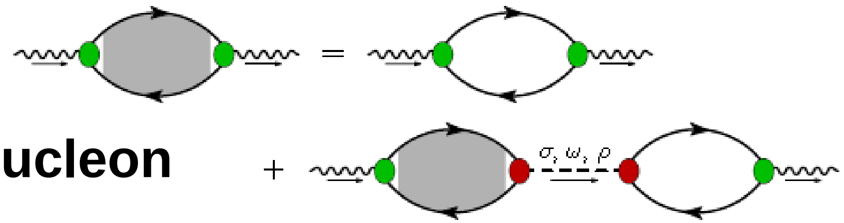
Parity violating EMC will test this at JLab 12 GeV

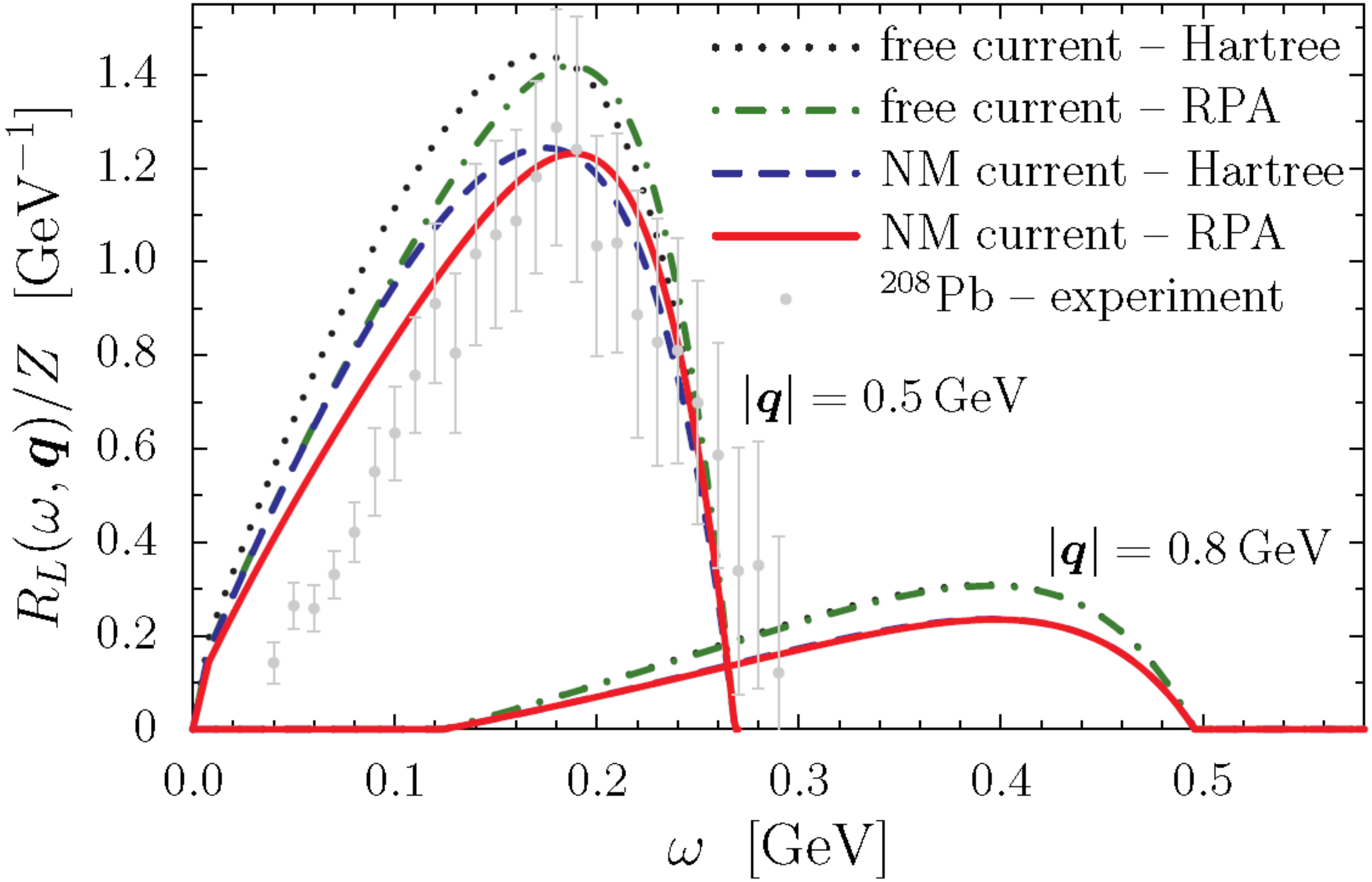
Modified Electromagnetic Form Factors In-Medium

Response Function

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

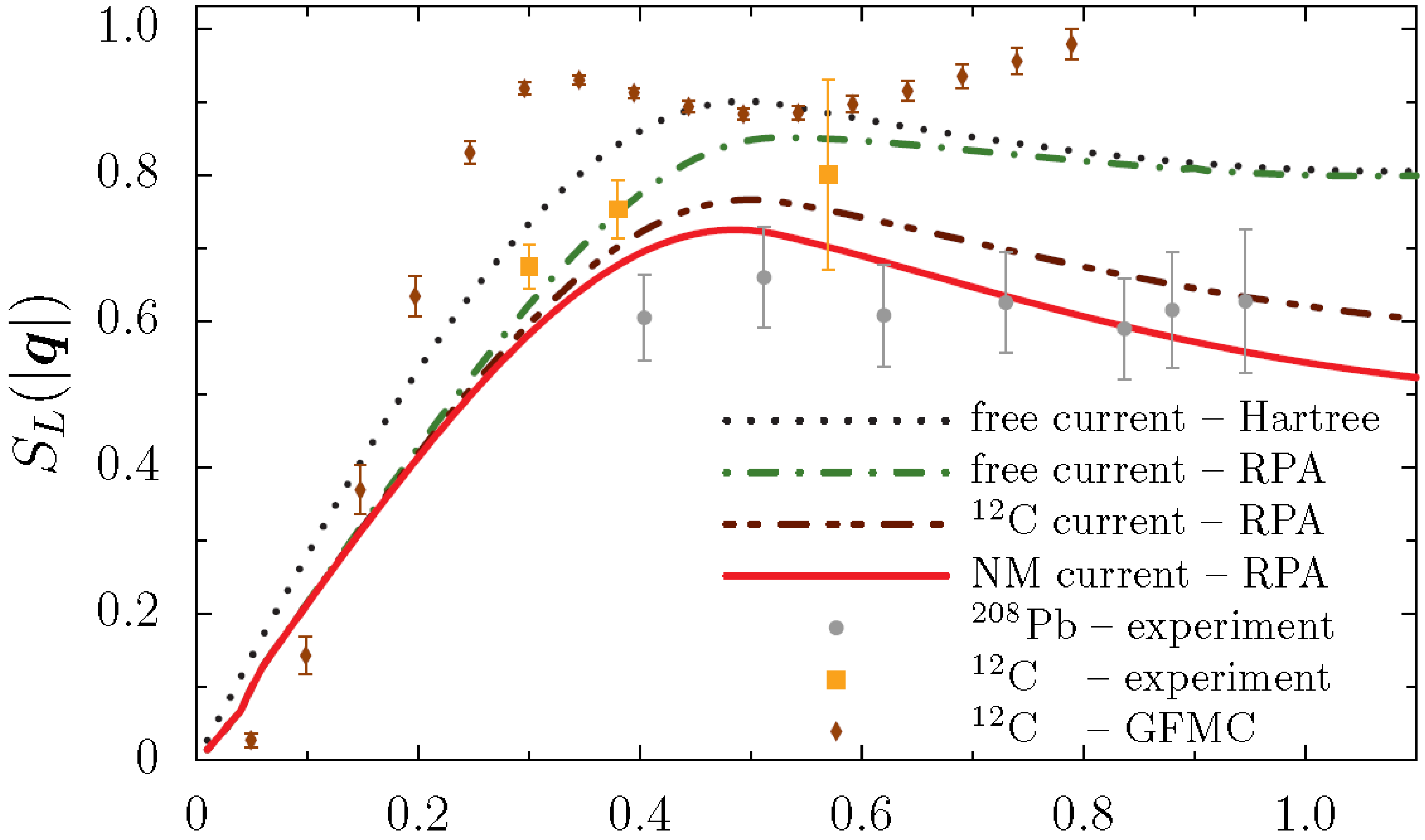
RPA correlations repulsive
Significant reduction in Response Function from modification of bound-nucleon





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

Comparison with Unmodified Nucleon & Data

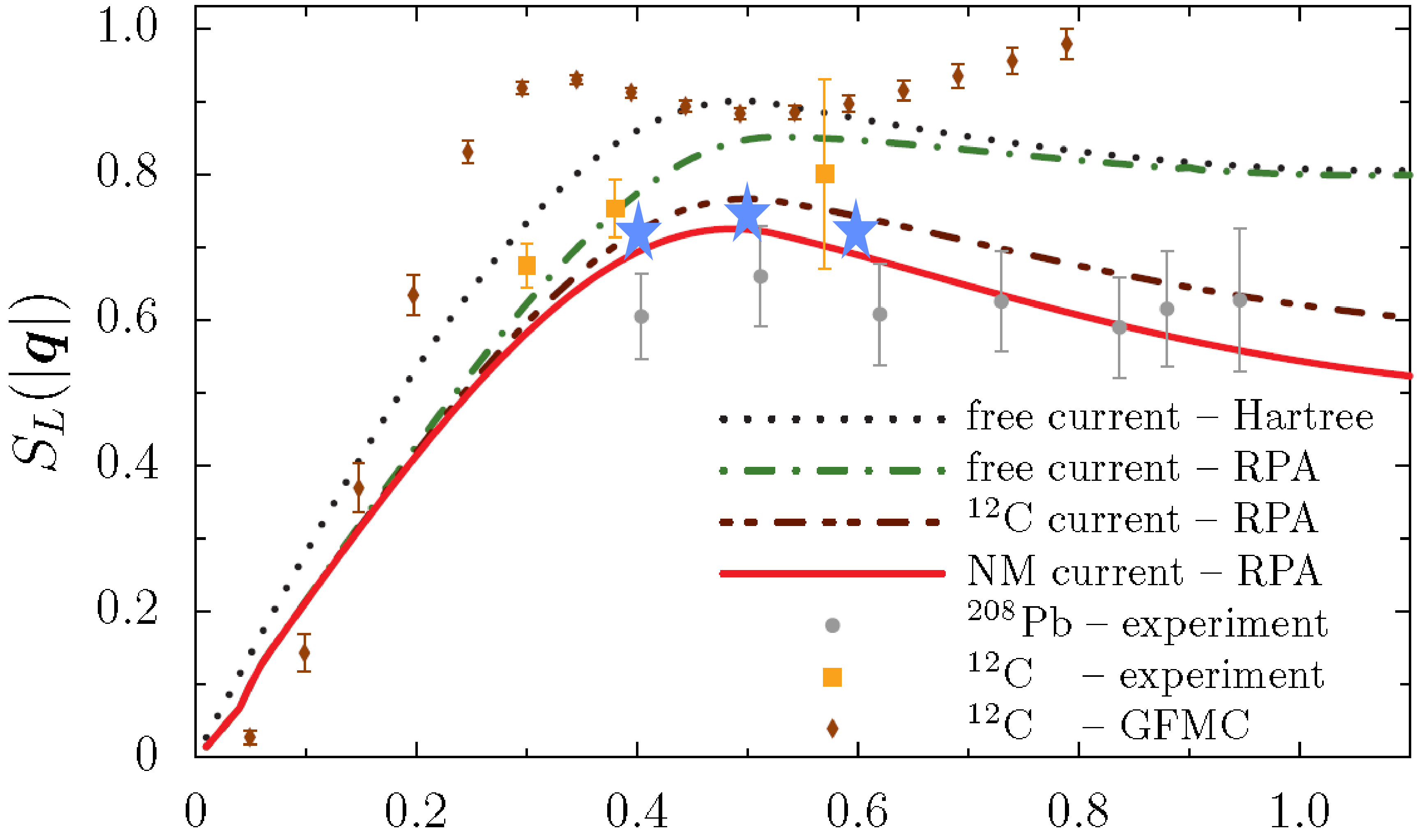


$$S_L(|\boldsymbol{q}|) = \int_{\omega+}^{|\boldsymbol{q}|} d\omega \, \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)}$$

Data: Morgenstern & Meziani

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

and these predictions are stable!



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

★ Saito *et al.*, QMC 1999 (*op cit*)

Data: Morgenstern & Meziani

Calculations: Cloët, Bentz & Thomas (PRL 116 arXiv:1506.05875)

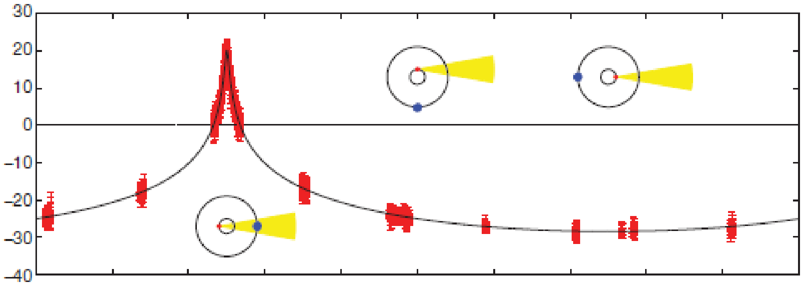
Neutron Stars

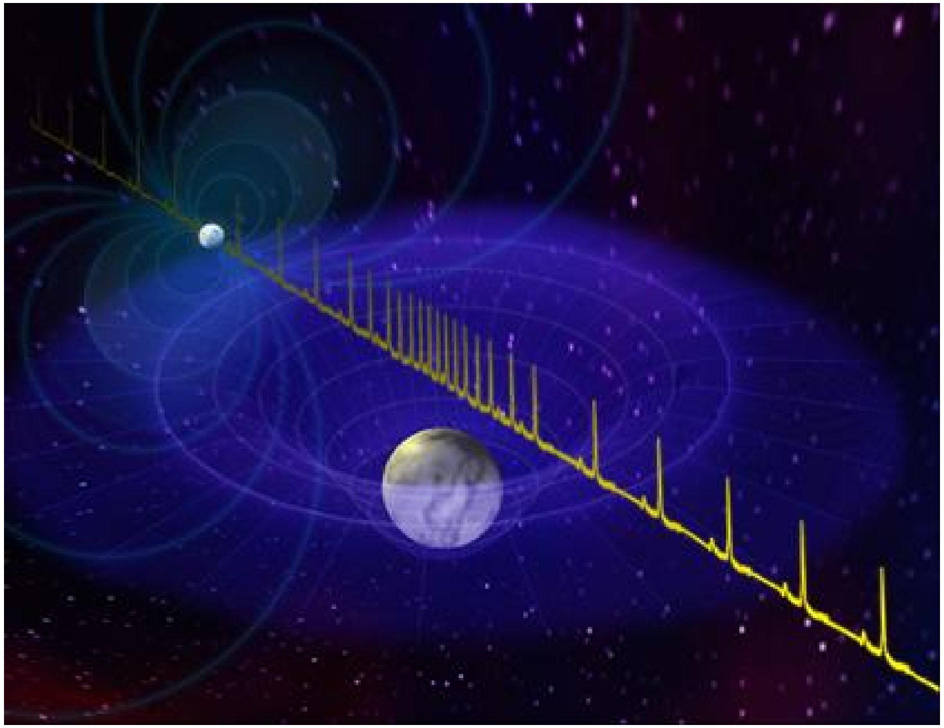
LETTER (2010)

doi:10.1038/nature09466

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]





Reports a very accurate pulsar mass much larger than seen before : 1.97 ± 0.04 solar mass

Claim: it rules out hyperon occurrence
- ignored our *published* work three years before!

J1614-2230

Hyperons

- Derive Λ N, Σ N, Λ Λ … effective forces in-medium
  with **no** additional free parameters
- Attractive and repulsive forces (σ and ω mean fields) both decrease as # light quarks decreases
- Predict: NO Σ hypernuclei are bound! **Agrees expt**
- Λ bound by ~30 MeV in nuclear matter (~Pb): **Agrees expt**
- Nothing (was) known about Ξ hypernuclei
  – JPARC **Progress**

Λ- and Ξ-Hypernuclei in QMC

	${}^{89}_{\Lambda}$Yb (Expt.)	${}^{91}_{\Lambda}$Zr	${}^{91}_{\Xi^0}$Zr	${}^{208}_{\Lambda}$Pb (Expt.)	${}^{209}_{\Lambda}$Pb	${}^{209}_{\Xi^0}$Pb
$1s_{1/2}$	-22.5	-24.0	-9.9	-27.0	-26.9	-15.0
$1p_{3/2}$		-19.4	-7.0		-24.0	-12.6
$1p_{1/2}$	-16.0 ($1p$)	-19.4	-7.2	-22.0 ($1p$)	-24.0	-12.7
$1d_{5/2}$		-13.4	-3.1	—	-20.1	-9.6
$2s_{1/2}$		-9.1	—	—	-17.1	-8.2
$1d_{3/2}$	-9.0 ($1d$)	-13.4	-3.4	-17.0 ($1d$)	-20.1	-9.8
$1f_{7/2}$		-6.5	—	—	-15.4	-6.2
$2p_{3/2}$		-1.7	—	—	-11.4	-4.2
$1f_{5/2}$	-2.0 ($1f$)	-6.4	—	-12.0 ($1f$)	-15.4	-6.5
$2p_{1/2}$		-1.6	—	—	-11.4	-4.3

Predicts Ξ – hypernuclei bound by 5-15 MeV − to be tested at J-PARC

"The first evidence of a bound state of Ξ^{-}–^{14}N system",
K. Nakazawa et al.,
Prog. Theor. Exp. Phys. (2015)

Guichon *et al*., Nucl.Phys. A814 (2008) 66; see also 1998

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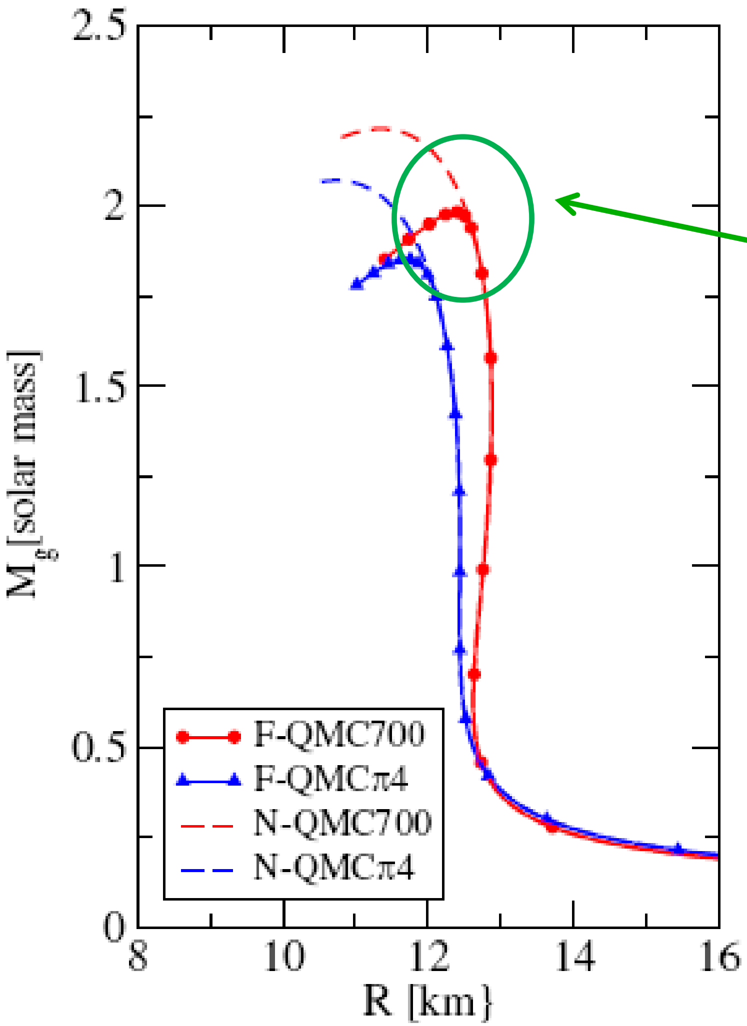
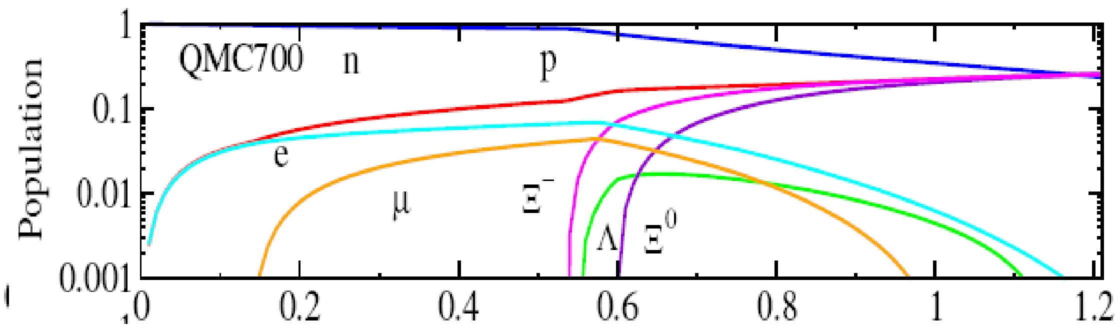
Consequences of QMC for Neutron Star



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.....

Light Dark Matter

Recently there was a very interesting proposal from Fornal and Grinstein (1801.01124).

Originated in long-standing puzzle concerning free neutron lifetime:

- **Measurement for trapped n's: 879.6 ± 0.6 sec**
- **Measurement in beam decay : 888.0 ± 2.0 sec**

This *3.5σ discrepancy* solved by existence of new decay mode, which would not be seen in the beam decay experiment

$$n \longrightarrow \text{Dark Matter } (\chi) + \text{something}$$

"Something" not a photon : Tang *et al*., Los Alamos 1802.01595

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Light Dark Matter (cont.)

- **There are very strict limits on the mass of the new DM particle. It should be within an MeV or so of the neutron mass. For the case**

$$n \longrightarrow \chi + \varphi$$

with χ carrying baryon number and φ also dark,

$$937.9 \text{ MeV} < m_\chi + m_\varphi < 939.565 \text{ MeV}$$

- **Serebrov *et al.,* 1802.06277 also claim this particle would resolve a reactor anti-neutrino anomaly**

- **Also nice discussion of tension with best value of neutron axial charge by Czarnecki *et al.,* 1802.01804 (constrains but does not rule out the explanation)**

Compatibility of Fornal-Grinstein Hypothesis with Neutron Star Properties?

- **In just 2 weeks a rush of papers**
  - **McKeen *et al.*, 1802.08244**
  - **Motta *et al.*, 1802.08427**
  - **Baym *et al.*, 1802.08282**
- **All reach a similar conclusion**
- **I follow the work of Motta, Guichon and Thomas (1802.08427)**
- **If such a dark matter particle exists neutrons high in the Fermi sea of a neutron star will be unstable**
- **This will replace high energy/pressure neutrons with lower energy/pressure dark matter particles: Consequences?**

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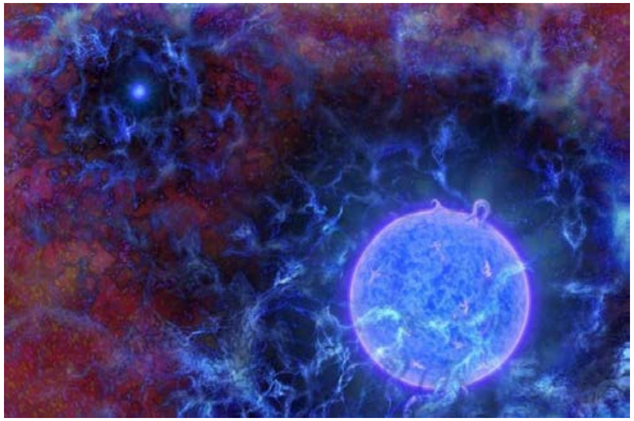
Also stimulating in view of a recent Nature article

- **Bowman *et al.* (Nature 555, 67-70 March 1st 2018) look at effect of star formation in the early Universe**

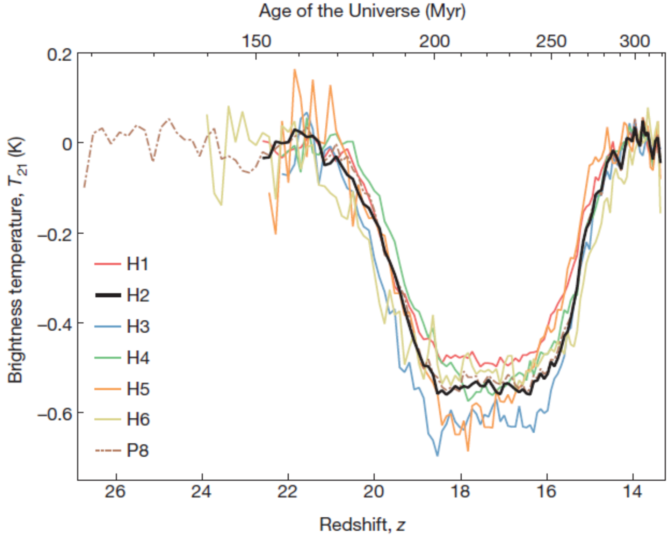
Astronomers detect signal from the dawn of the universe, using simple antenna in WA outback



- **Dark matter can explain the absorption at the hydrogen 21cm line IF it has**

  mass < few GeV

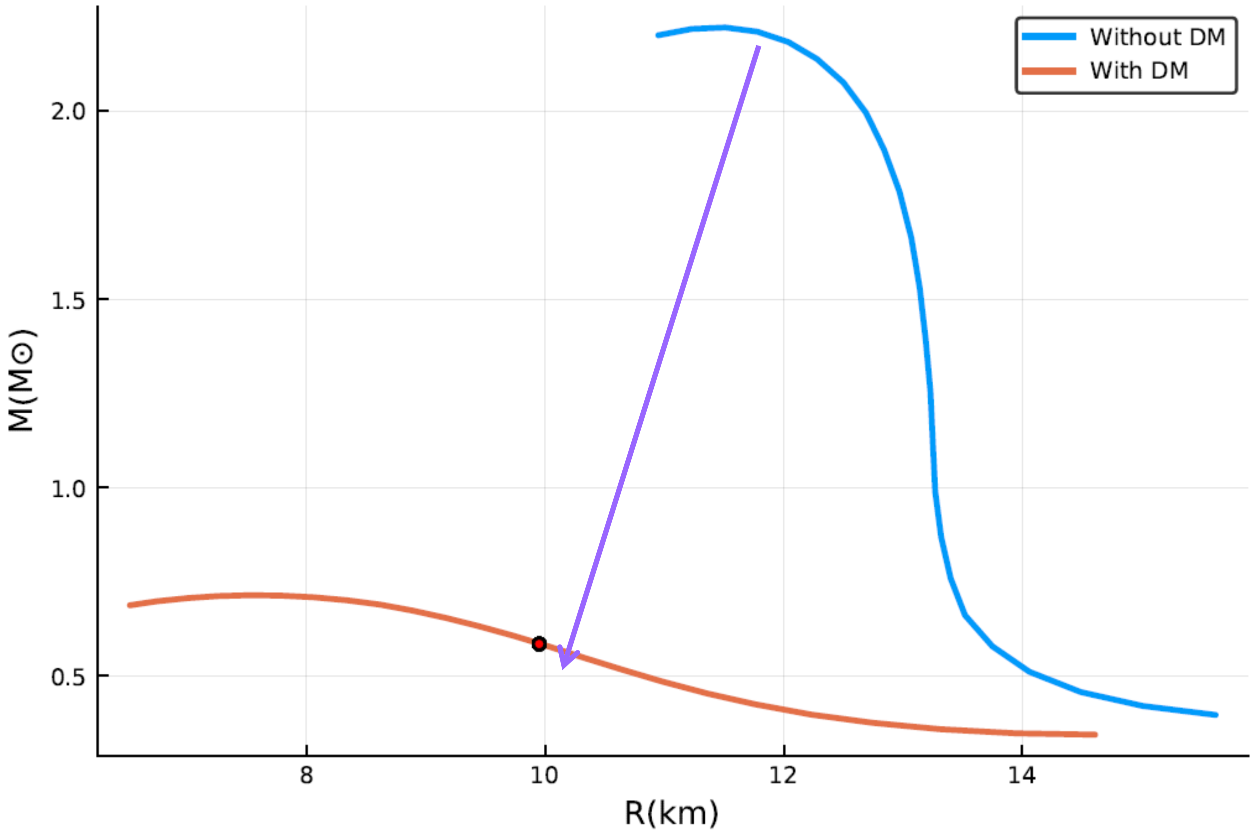
  and $\sigma > 10^{-21}$ cm^2



Solve Tolman-Oppenheimer-Volkoff Equations

- **Maximum allowed mass for stable neutron star drops from 2.21 $M_\odot$ to 0.7 $M_\odot$**

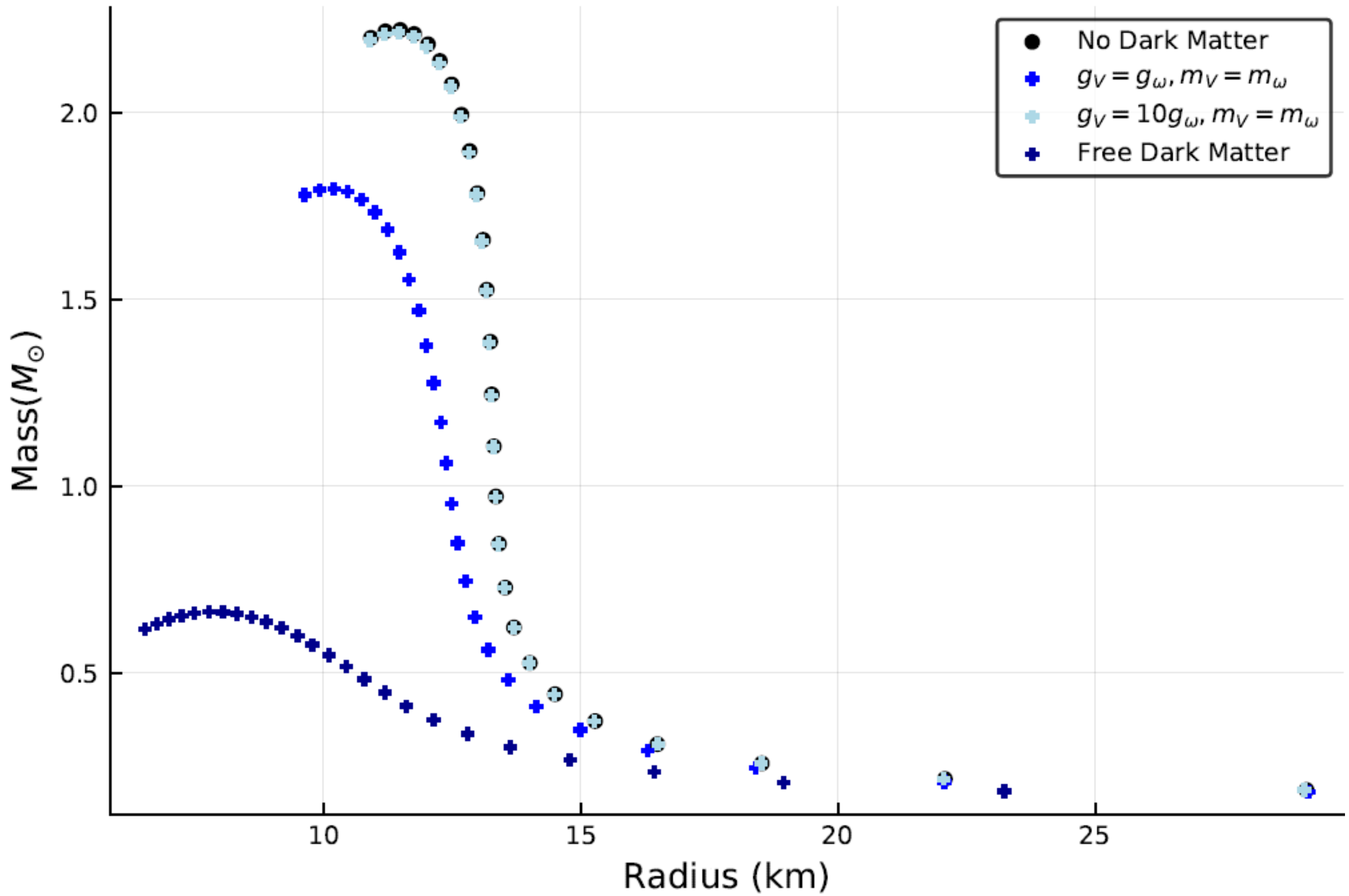
- **But cannot even get that as maximum stable star goes to just 0.58 $M_\odot$**



Motta et al., J. Phys. G45 (2018) no.5, 05LT01

Is there a way out?

- **If the dark matter has a strong repulsive interaction with other dark matter we can lift the pressure and hence the maximum neutron star mass**



Motta et al., Conf. on Particles and Cosmology Singapore 2018 - arXiv:1806.00903

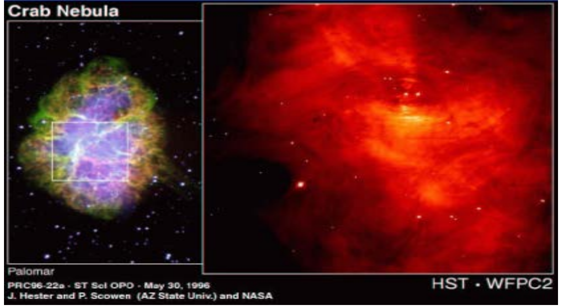
GW170817: Measurements of neutron star radii and equation of state

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

arXiv:1805.11581

I. Summary



- Intermediate range NN attraction is STRONG Lorentz scalar

- This modifies the intrinsic structure of the bound nucleon
  - profound change in shell model :

  what occupies shell model states are NOT free nucleons

- Scalar polarizability is a natural source of three-body forces (NNN, HNN, HHN…)
  - clear physical interpretation

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

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II. Summary

- **Initial systematic study of finite nuclei very promising**
  - Binding energies typically within 0.3% across periodic table
  - Super-heavies ($Z > 100$) especially good
- **Need empirical confirmation:**
  - Response Functions & Coulomb sum rule (soon?)
  - Isovector EMC effect; spin EMC (not too long?)
- **Yields neutron stars at $2M_{\odot}$ *with hyperons***
- **Unfortunately existence of neutron stars means that the nice idea to resolve τ_n anomaly in terms of decay to dark matter is incorrect**

Special Mentions……

Guichon

Tsushima

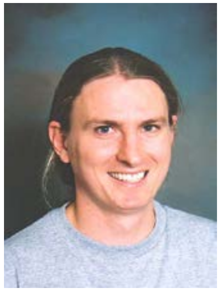
Saito

Stone

Krein

Bentz

Matevosyan



Cloët

Whittenbury

Simenel

Martinez

Motta

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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

Hadrons in medium

No new parameters....

Guidance from Zweig rule
→ no meson coupling to strange quark
which also couples to the nucleon

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Cascade Hypernuclei Important

K. Tsushima et al. / Nuclear Physics A 630 (1998) 691–718 711

Table 6

Single-particle energies (in MeV) for ${}^{17}_{Y}$O, ${}^{41}_{Y}$Ca and ${}^{49}_{Y}$Ca hypernuclei, calculated with the effective Pauli blocking and the $\Sigma N - \Lambda N$ channel coupling. Experimental data are taken from Ref. [34]. Spin–orbit splittings are not well determined by the experiments

	${}^{16}_{\Lambda}$O (Expt.)	${}^{17}_{\Lambda}$O	${}^{17}_{\Sigma^-}$O	${}^{17}_{\Sigma^0}$O	${}^{17}_{\Sigma^+}$O	${}^{17}_{\Xi^-}$O	${}^{17}_{\Xi^0}$O
$1s_{1/2}$	−12.5	−14.1	−17.2	−9.6	−3.3	−9.9	−4.5
$1p_{3/2}$		−5.1	−8.7	−3.2	–	−3.4	–
$1p_{1/2}$	−2.5 (1p)	−5.0	−8.0	−2.6	–	−3.4	–

The first evidence of a bound state of Ξ^--^{14}N system"K.Nakazawa et al., Prog. Theor. Exp. Phys. (2015)

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Explicit Demonstration of Origin of 3-Body Force

Since early 70's tremendous amount of work in nuclear theory is based upon effective forces

- **Used for everything from nuclear astrophysics to collective excitations of nuclei**
- **Skyrme Force: Vautherin and Brink**

$$H_{QMC} = \sum_i \frac{\overleftarrow{\nabla}_i . \overrightarrow{\nabla}_i}{2M} + \frac{G_\sigma}{2M^2} \sum_{i \neq j} \overleftarrow{\nabla}_i \delta(\vec{R}_{ij}) . \overrightarrow{\nabla}_i$$

$$+ \frac{1}{2} \sum_{i \neq j} \left[\nabla_i^2 \delta(\vec{R}_{ij}) \right] \left[\frac{G_\omega}{m_\omega^2} - \frac{G_\sigma}{m_\sigma^2} + \frac{G_\rho}{m_\rho^2} \frac{\vec{\tau}_i . \vec{\tau}_j}{4} \right]$$

$$+ \frac{1}{2} \sum_{i \neq j} \delta(\vec{R}_{ij}) \left[G_\omega - G_\sigma + G_\rho \frac{\vec{\tau}_i . \vec{\tau}_j}{4} \right]$$

$$+ \frac{d G_\sigma^2}{2} \sum_{i \neq j \neq k} \delta^2(ijk) - \frac{d^2 G_\sigma^3}{2} \sum_{i \neq j \neq k \neq l} \delta^3(ijkl)$$

$$+ \frac{i}{4M^2} \sum_{i \neq j} A_{ij} \overleftarrow{\nabla}_i \delta(\vec{R}_{ij}) \times \overrightarrow{\nabla}_i . \vec{\sigma}_i \, ,$$

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Guichon and Thomas, Phys. Rev. Lett. 93, 132502 (2004)

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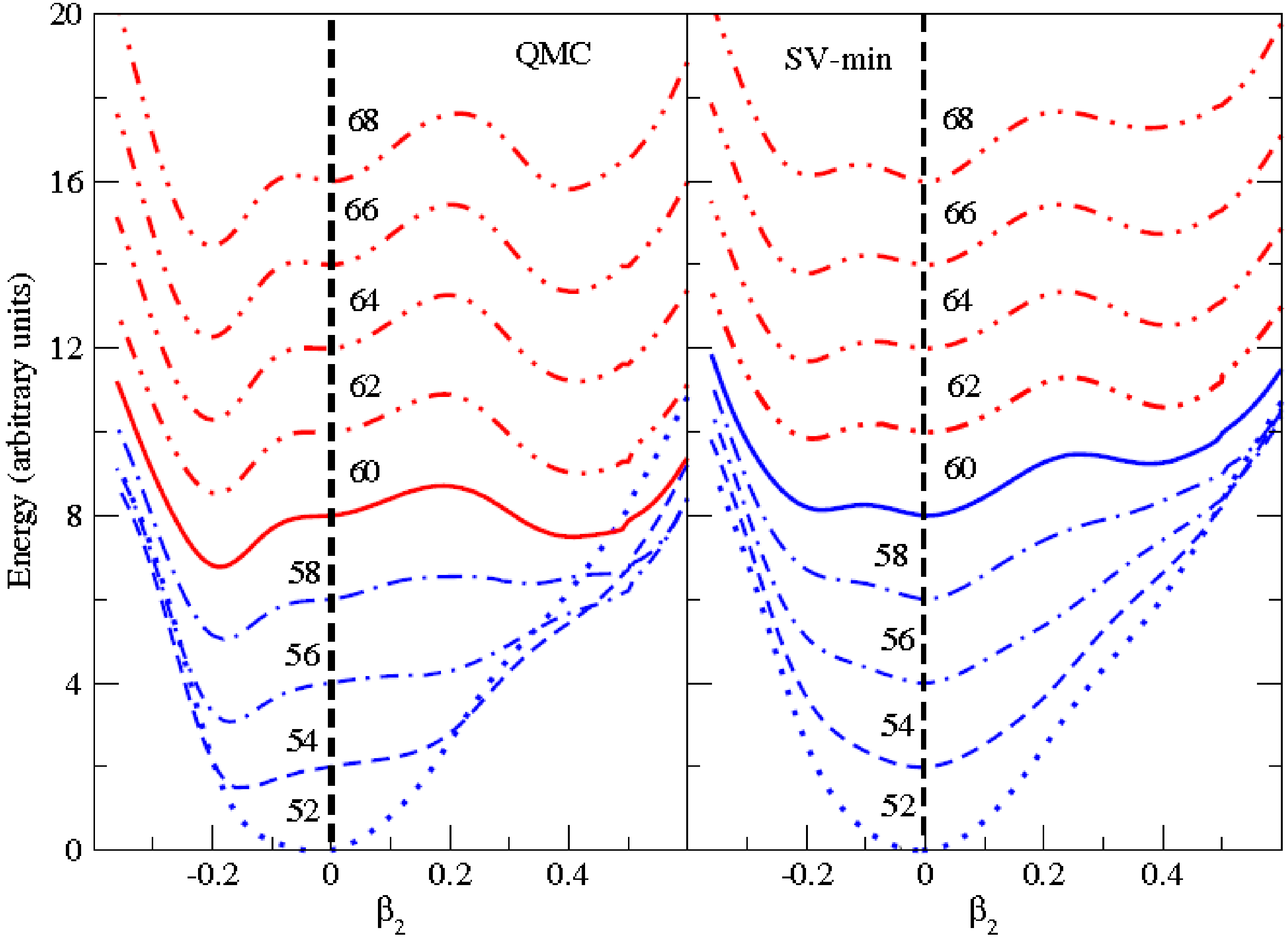
Spin-orbit splitting

Element		States	Exp [keV]	QMC [keV]	SV-bas [keV]
O16	proton	$1p_{1/2}$ - $1p_{3/2}$	6.3 (1.3)a)	5.8	5.0
	neutron	$1p_{1/2}$ - $1p_{3/2}$	6.1 (1.2)a)	5.7	5.1
Ca40	proton	$1d_{3/2}$ - $1d_{5/2}$	7.2 [b)]	6.3	5.7
	neutron	$1d_{3/2}$ - $1d_{5/2}$	6.3 [b)]	6.3	5.8
Ca48	proton	$1d_{3/2}$ - $1d_{5/2}$	4.3 [b)]	6.3	5.2
	neutron	$1d_{3/2}$ - $1d_{5/2}$		5.3	5.2
Sn132	proton	$2p_{1/2}$ - $2p_{3/2}$	1.35(27)[a)]	1.32	1.22
	neutron	$2p_{1/2}$ - $2p_{3/2}$	1.65(13)[a)]	1.47	1.63
	neutron	$2d_{3/2}$ - $2d_{5/2}$		2.71	2.11
Pb208	proton	$2p_{1/2}$ - $2p_{3/2}$		0.91	0.93
	neutron	$3p_{1/2}$ - $3p_{3/2}$	0.90(18)[a)]	1.11	0.89

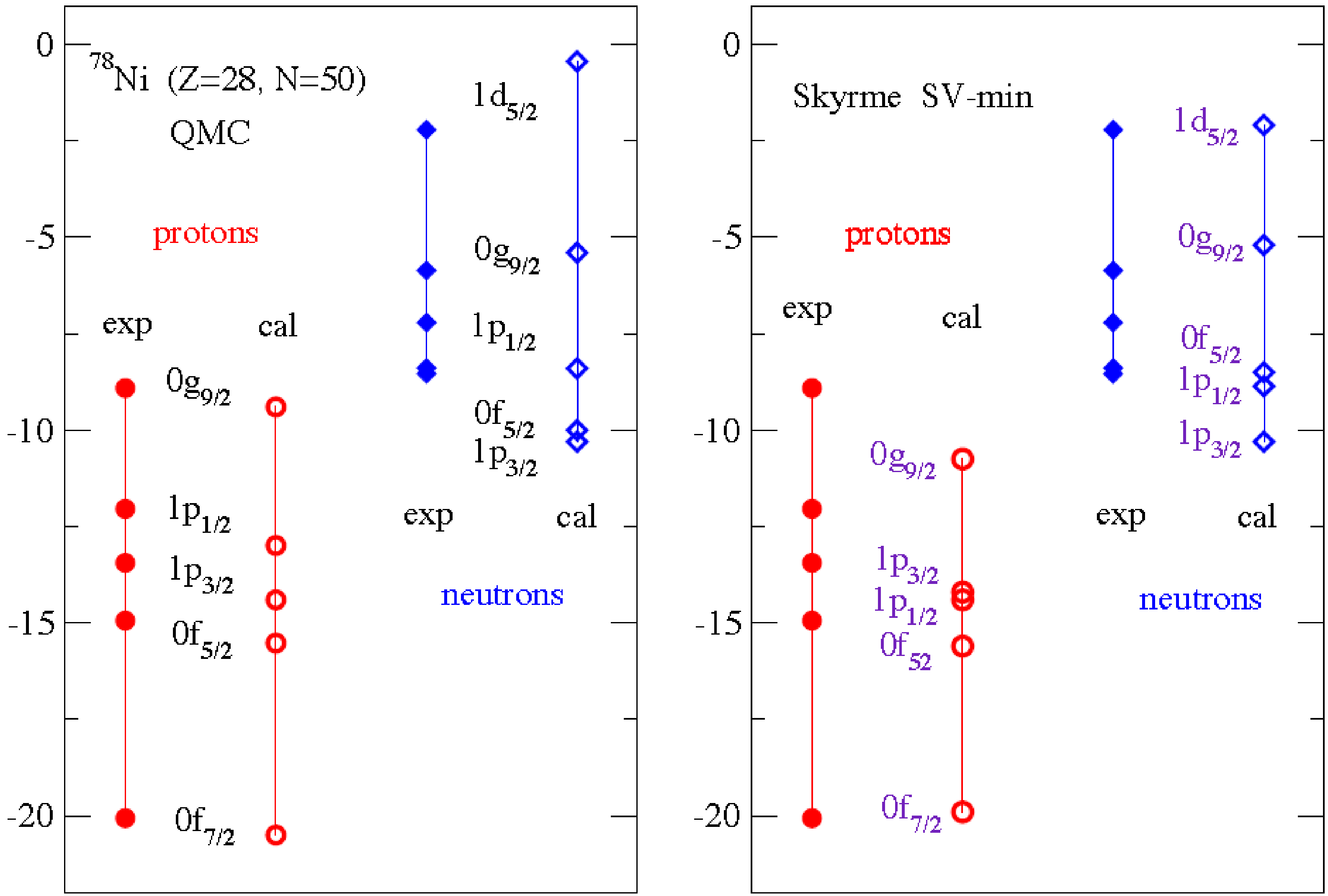
Shape evolution of Zr (Z=40) Isotopes



- Shape co-existence sets in at N=60 – Sotty *et al*.,PRL115 (2015)172501
- Usually difficult to describe
  - – e.g. Mei et al., PRC85, 034321 (2012)

Stone et al., PRL 116 (2016) 092501

“Hot off the press”



Traditionally very hard to describe

Global search on Skyrme forces

The Skyrme Interaction and Nuclear Matter Constraints

Phys. Rev. C85 (2012) 035201

M. Dutra, O. Lourenço, J. S. S. Martins, and A. Delfino

Departamento de Física - Universidade Federal Fluminense,

Av. Litorânea s/n, 24210-150 Boa Viagem, Niterói RJ, Brazil

J. R. Stone

Department of Physics, University of Oxford,

OX1 3PU Oxford, United Kingdom and

Department of Physics and Astronomy,

University of Tennessee, Knoxville, Tennessee 37996, USA

C. Providência

Centro de Física Computacional,

Department of Physics,

University of Coimbra,

P-3004-516 Coimbra, Portugal

These authors tested 233 widely used Skyrme-type forces against 12 standard nuclear properties: only 17 survived including two QMC potentials

Furthermore, we considered weaker constraints arising from giant resonance experiments on isoscalar and isovector effective nucleon mass in SNM and BEM, Landau parameters and low-mass neutron stars. If these constraints are taken into account, the number of CSkP reduces to to 9, GSkI, GSkII, KDE0v1, LNS, NRAPR, QMC700, QMC750 and SKRA, the CSkP* list.

Truly remarkable – force derived from quark level does a better job of fitting nuclear structure constraints than phenomenological fits with many times # parameters!

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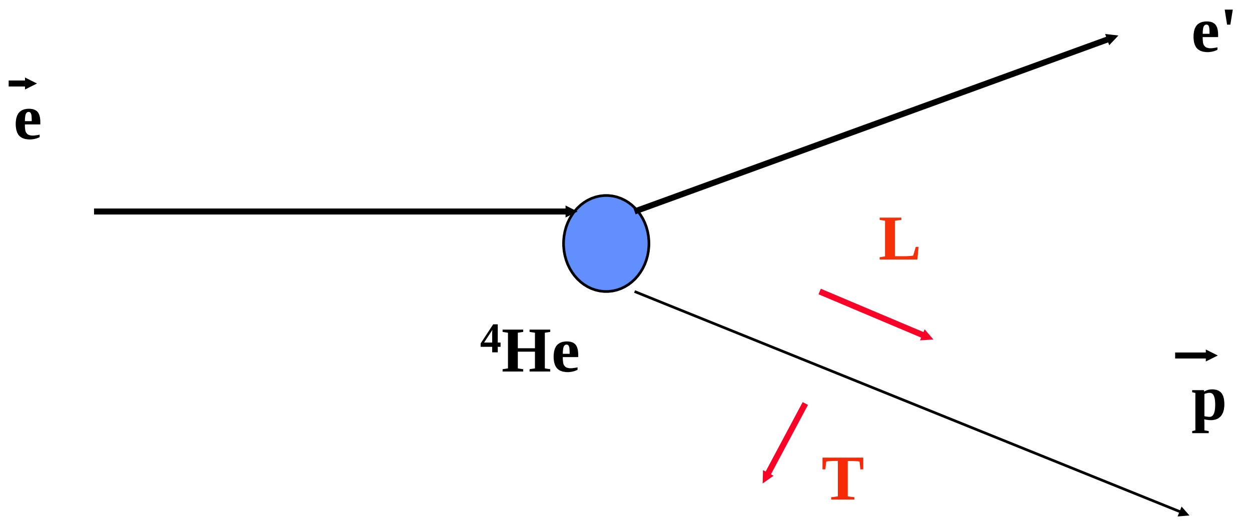
Experimental Test of QMC at Mainz & JLab*

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

ELSEVIER

22 January 1998

PHYSICS LETTERS B

Physics Letters B 417 (1998) 217–223

In-medium electron-nucleon scattering

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

[a] *Department of Physics and Mathematical Physics and Special Research Centre for the Subatomic Structure of Matter, University of Adelaide, Australia 5005*

[b] *Physics Division, Tohoku College of Pharmacy, Sendai 981, Japan*

In-medium nucleon electromagnetic form factors are calculated in the quark meson coupling model. The form factors are typically found to be suppressed as the density increases. For example, at normal nuclear density and $Q^2 \sim 0.3$ GeV^2, the nucleon electric form factors are reduced by approximately 8% while the magnetic form factors are reduced by only 1–2%. These variations are consistent with current experimental limits but should be tested by more precise experiments in the near future. © 1998 Elsevier Science B.V.

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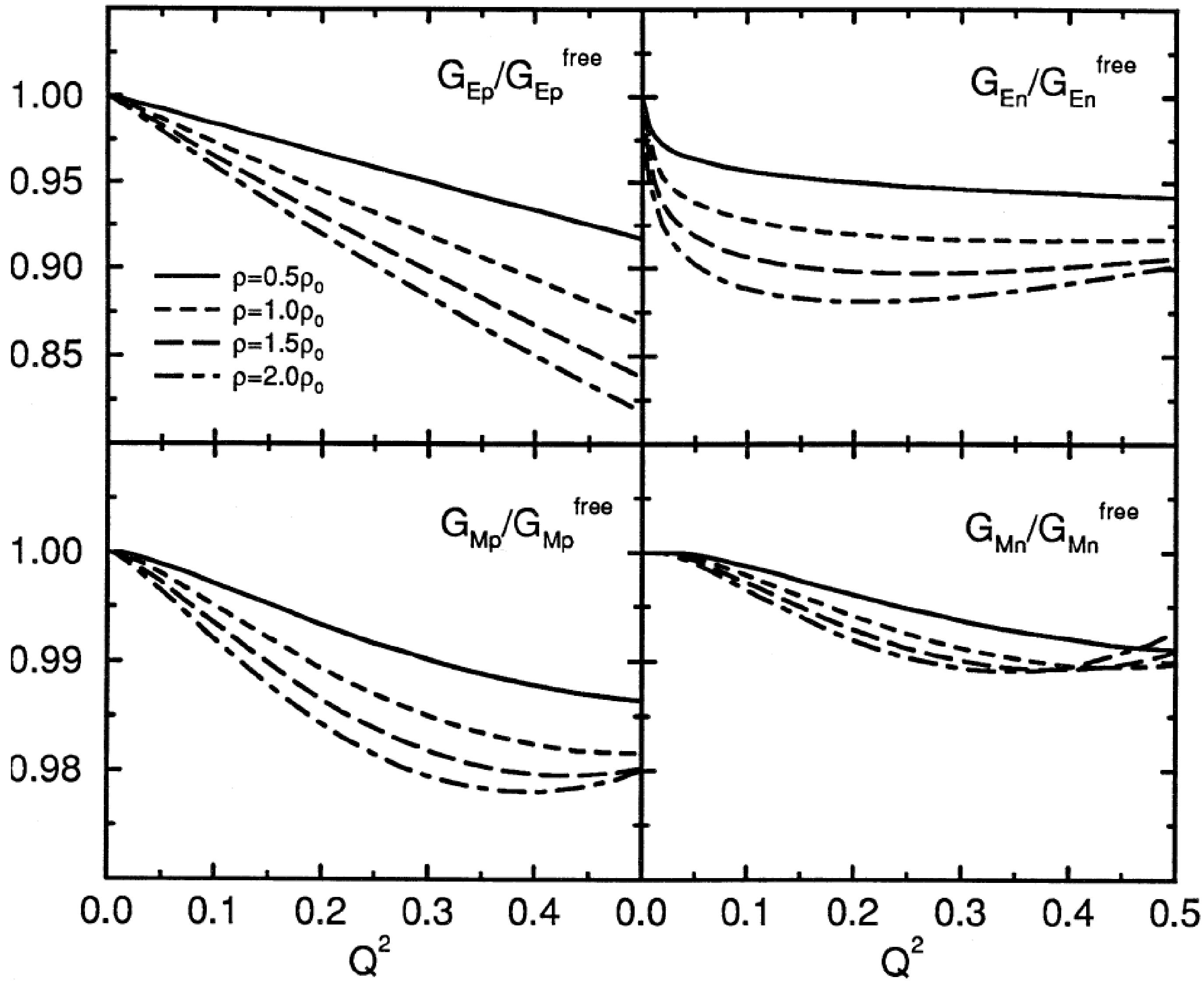
Archival

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

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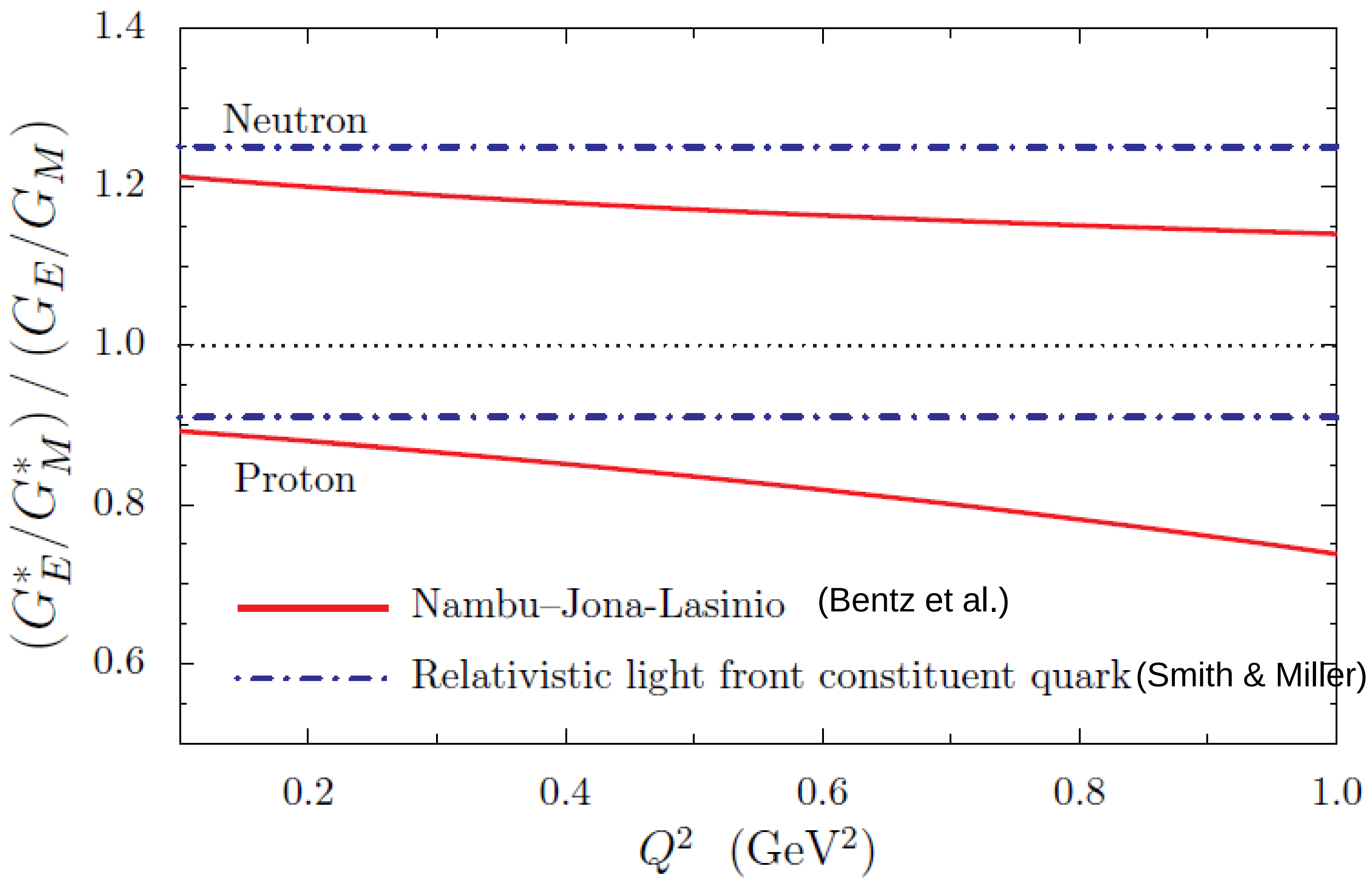
Super-ratio – in-medium to free space

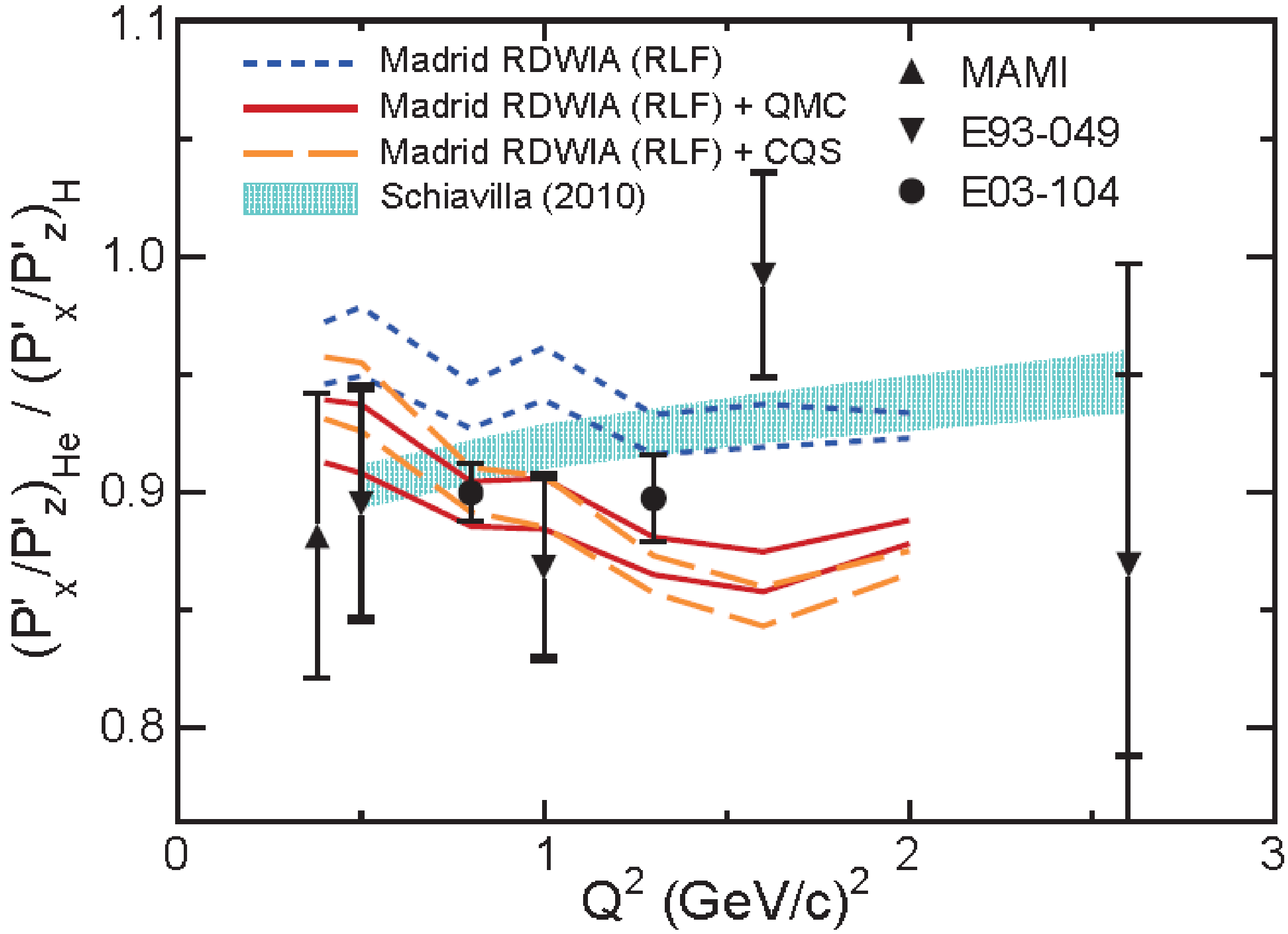


from - Cloet, Miller et al., arXiv:0903.1312

Jefferson Lab & Mainz : more from S. Strauch

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)

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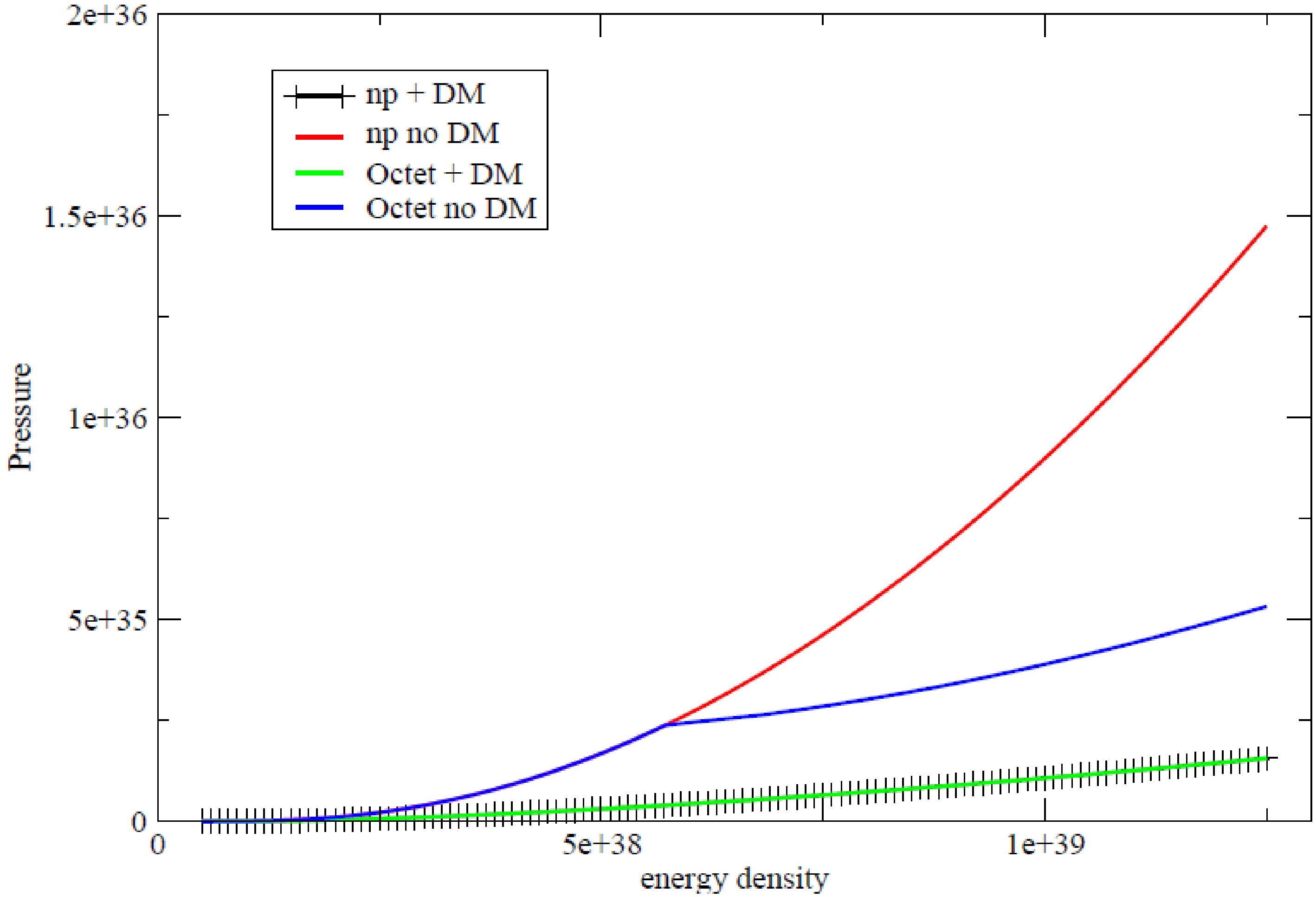
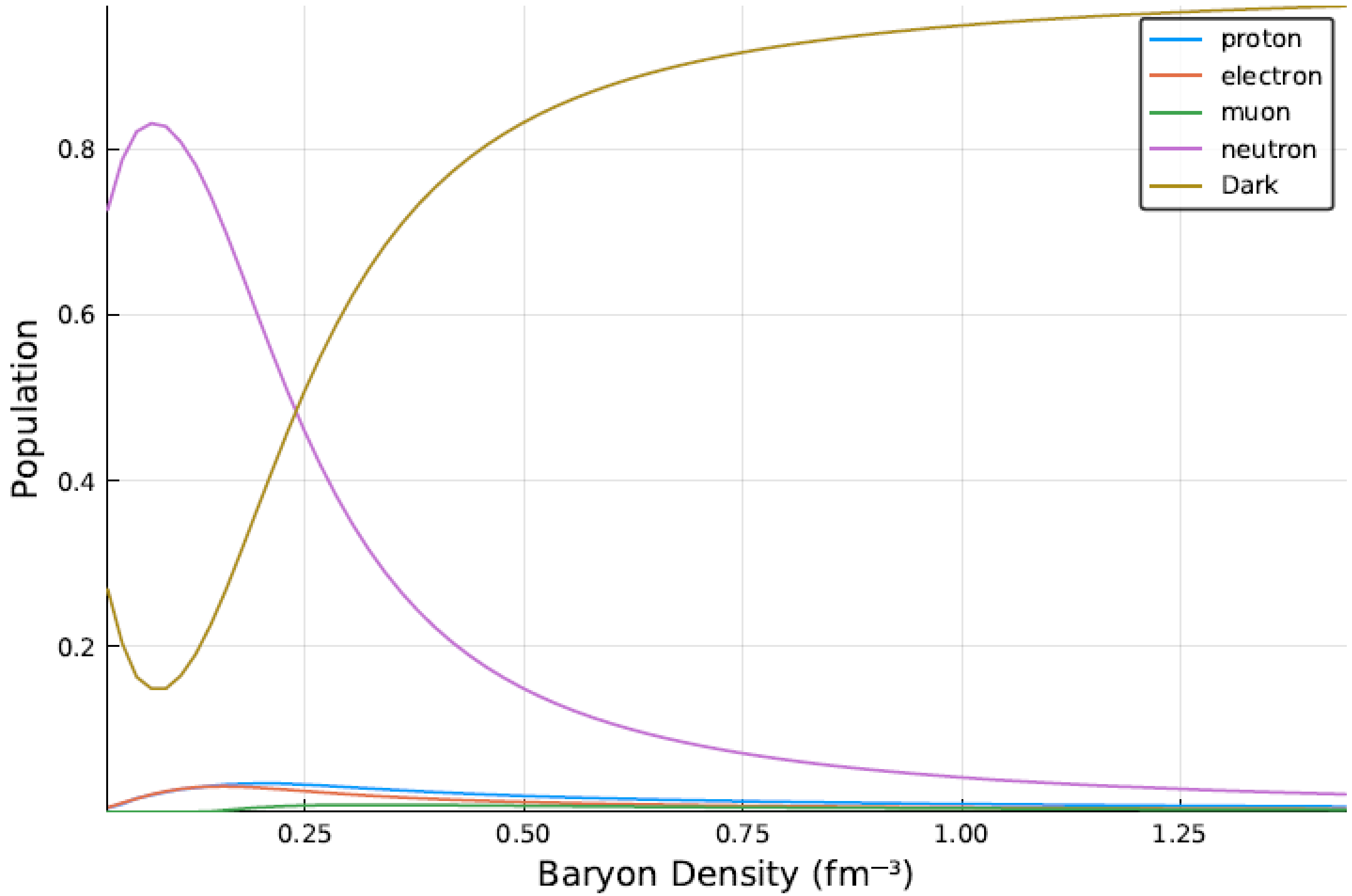
Including hyperons has no significant effect



Species fractions



Motta et al., 1802.08427

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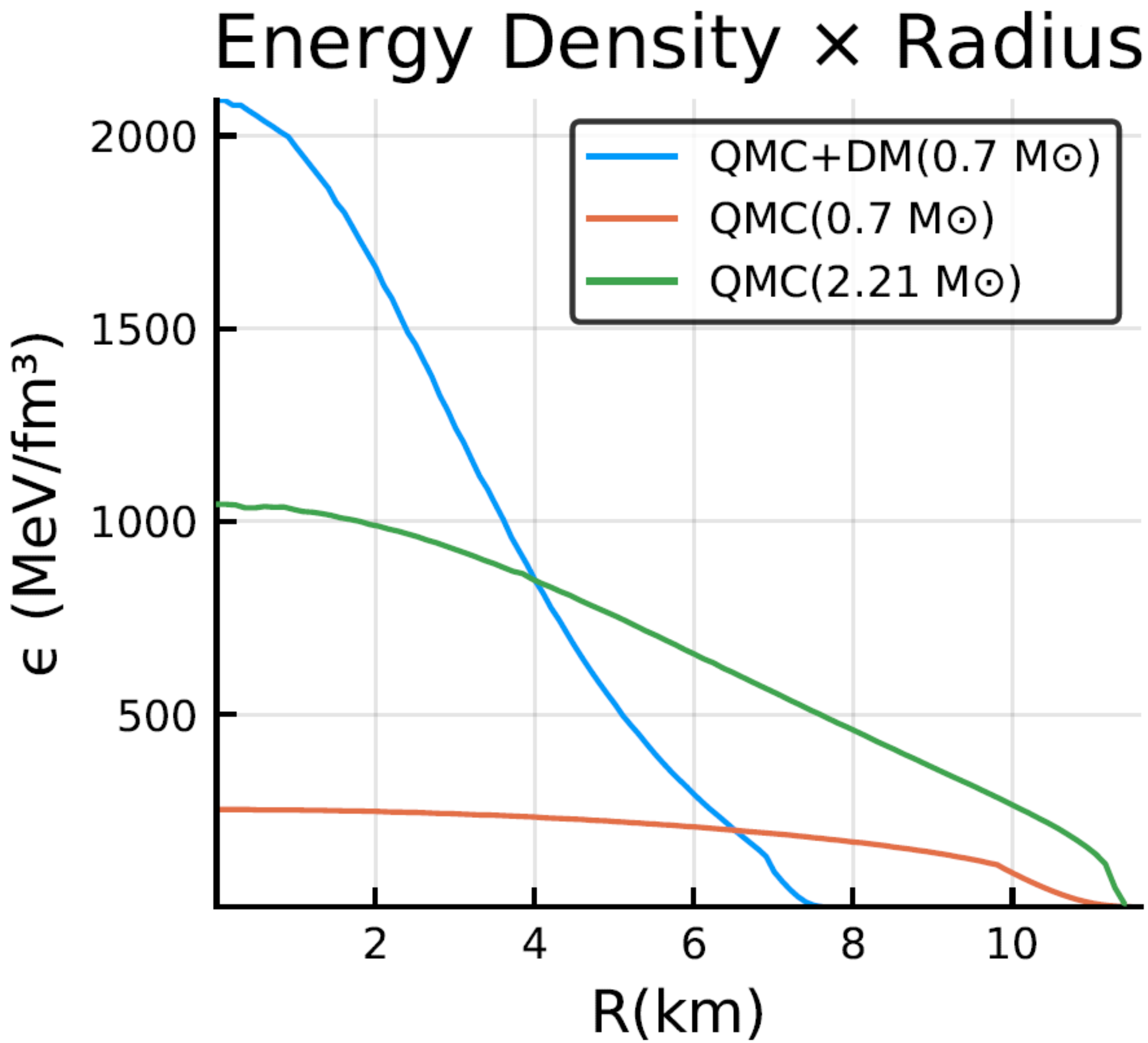
Complete change in structure



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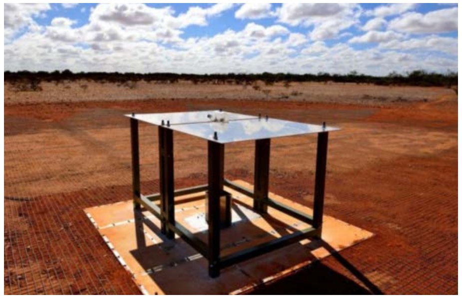
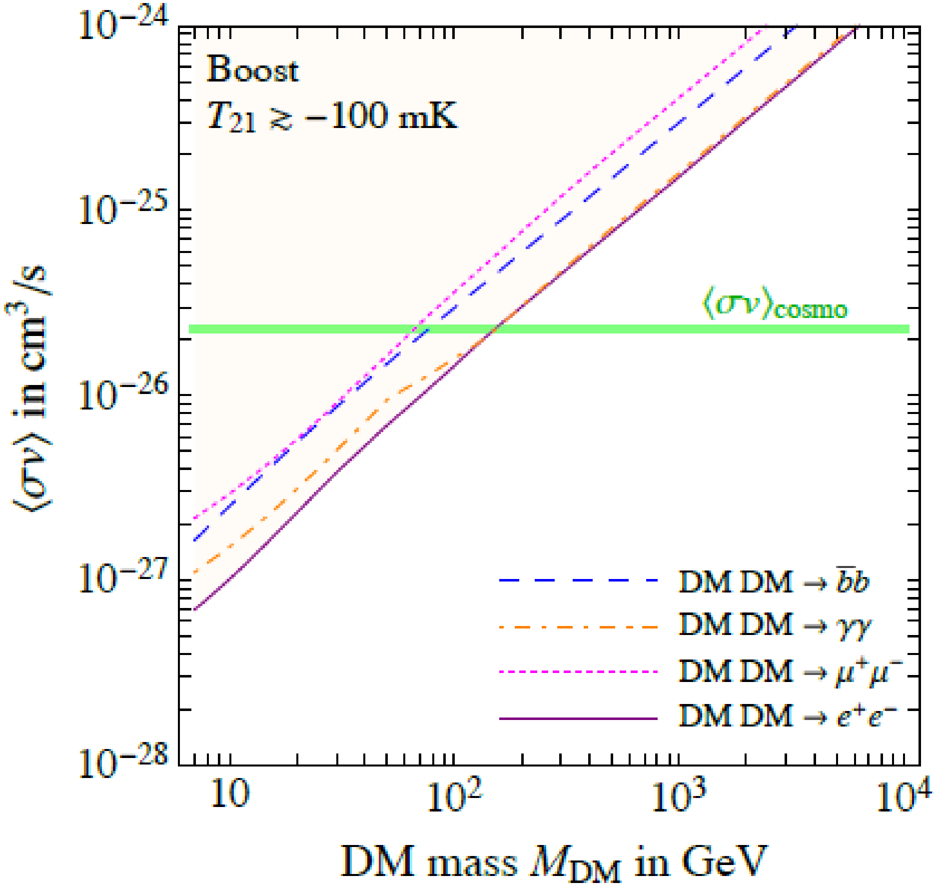
Very recent analysis of 21cm data: arXiv:1803.03629



Bounds on Dark Matter annihilations from 21 cm data

Guido D'Amico[a], Paolo Panci[a], Alessandro Strumia[a,b,c]



Hence: unlikely that interaction of DM with itself would save it!

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Can we Measure Scalar Polarizability in Lattice QCD ?

- IF we can, then in a real sense we would be linking nuclear structure to QCD itself, because scalar polarizability is sufficient in simplest, relativistic mean field theory to produce saturation

- Initial ideas on this published :
  the trick is to apply a chiral invariant scalar field
  − do indeed find polarizability opposing applied σ field

18th Nishinomiya Symposium: nucl-th/0411014
− published in Prog. Theor. Phys.

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