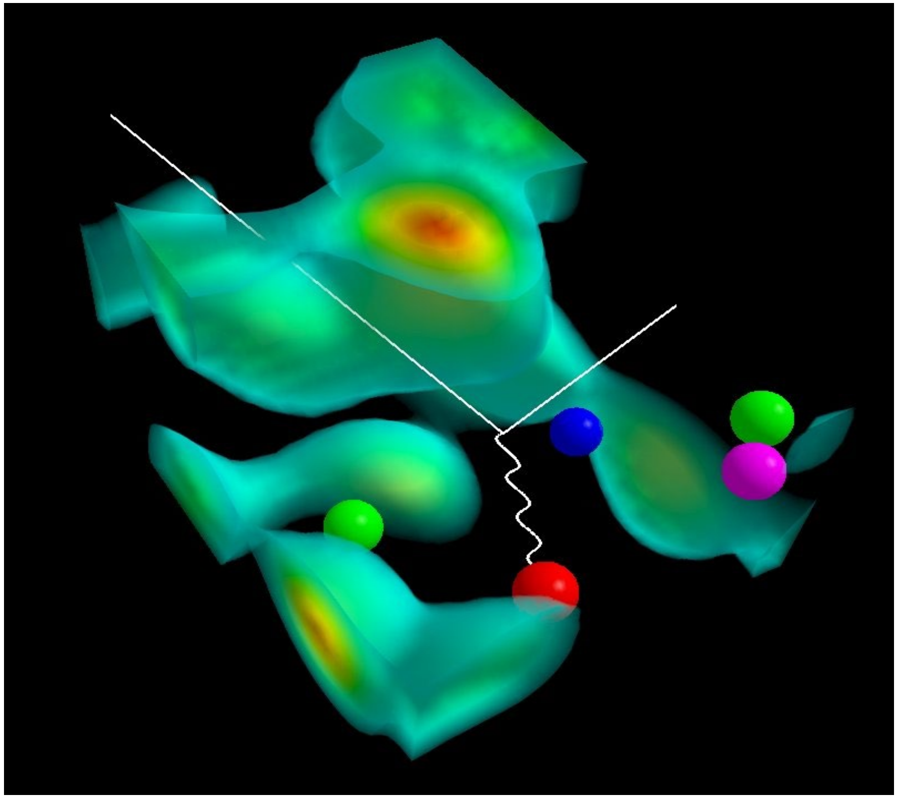
The QMC Model: From Quarks to Nuclear Structure and Neutron Stars



Anthony W. Thomas

ADELAIDE UNIVERSITY AUSTRALIA

INT Colloquium
1st February 2022

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. Recent results for finite nuclei

IV. Neutron Stars: 2 solar masses *with* hyperons
  – <u>before</u> they were discovered

I. Insights into nuclear structure

– 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 (EIC motivation)**

- **"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"**

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DARK MATTER PARTICLE PHYSICS

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

What do we know?

- **Since 1970s: Dispersion relations told us that 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!!**

Very large scalar mean-fields are a fact

1970 R. BROCKMANN AND R. MACHLEIDT

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 captured by EFT with N and π alone**

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**

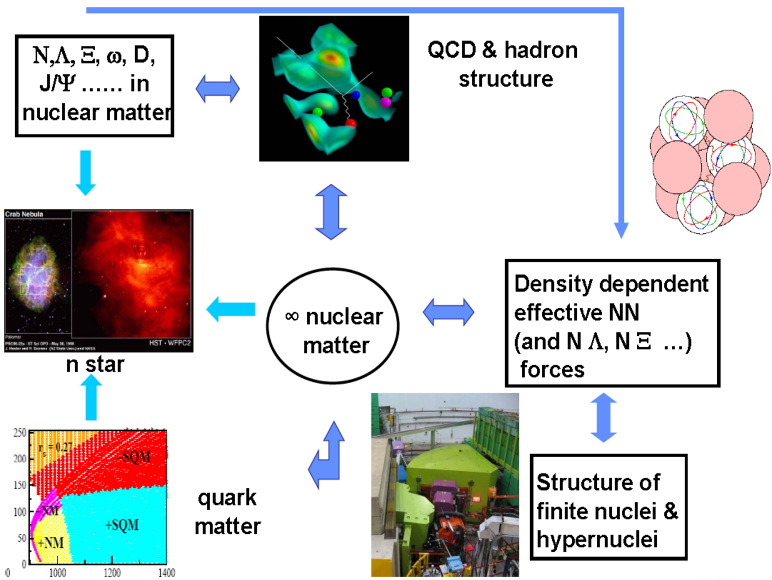
- **Hence, initially <u>only 4 parameters</u>**

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

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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 <u>EFFICIENT BECAUSE QUARKS ARE LIGHT</u>)

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

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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

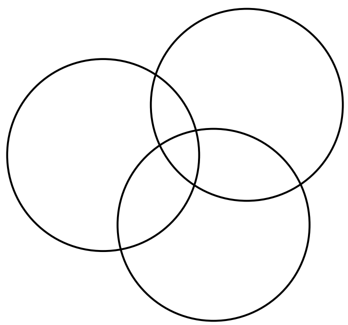
$$M^*(\vec{r}) = M - g_\sigma \sigma(\vec{r}) + \frac{d}{2}\left(g_\sigma \sigma(\vec{r})\right)^2$$

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.

Summary : Scalar Polarizability

- 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 (NNN, HNN, HHN…) generated with NO new parameters
  – critical in neutron stars

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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 density functional:**

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

Derivation of EDF (cont.)

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

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

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

$$+ p \leftrightarrow n,$$

$$\mathcal{H}_{\text{fin}} = \left[\left(\frac{3G_\rho}{32m_\rho{}^2} - \frac{3G_\sigma}{8m_\sigma{}^2} + \frac{3G_\omega}{8m_\omega{}^2} - \frac{G_\sigma}{8M_N{}^2} \right) \rho_n \right.$$

$$\left. + \left(\frac{-3G_\rho}{16m_\rho{}^2} - \frac{G_\sigma}{2m_\sigma{}^2} + \frac{G_\omega}{2m_\omega{}^2} - \frac{G_\sigma}{4M_N{}^2} \right) \rho_p \right] \nabla^2(\rho_n) + p \leftrightarrow n,$$

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

$$\left. + \left(\frac{-G_\sigma}{4M_N{}^2} + \frac{G_\omega(1-2\mu_s)}{4M_N{}^2} \right) \rho_p \right] + p \leftrightarrow n.$$

Spin-orbit force predicted!

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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**

$$-17 < E/A < -15 \text{ MeV}$$
$$0.14 < \rho_0 < 0.18 \text{ fm}^{-3}$$
$$28 < S_0 < 34 \text{ MeV}$$
$$L > 20 \text{ MeV}$$
$$250 < K_0 < 350 \text{ MeV}$$

- **Fix at overall best description of finite nuclei with 5 parameters** (3 for the EDF +2 pairing pars)

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

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Overview of 106 Nuclei Studied – Across Periodic Table

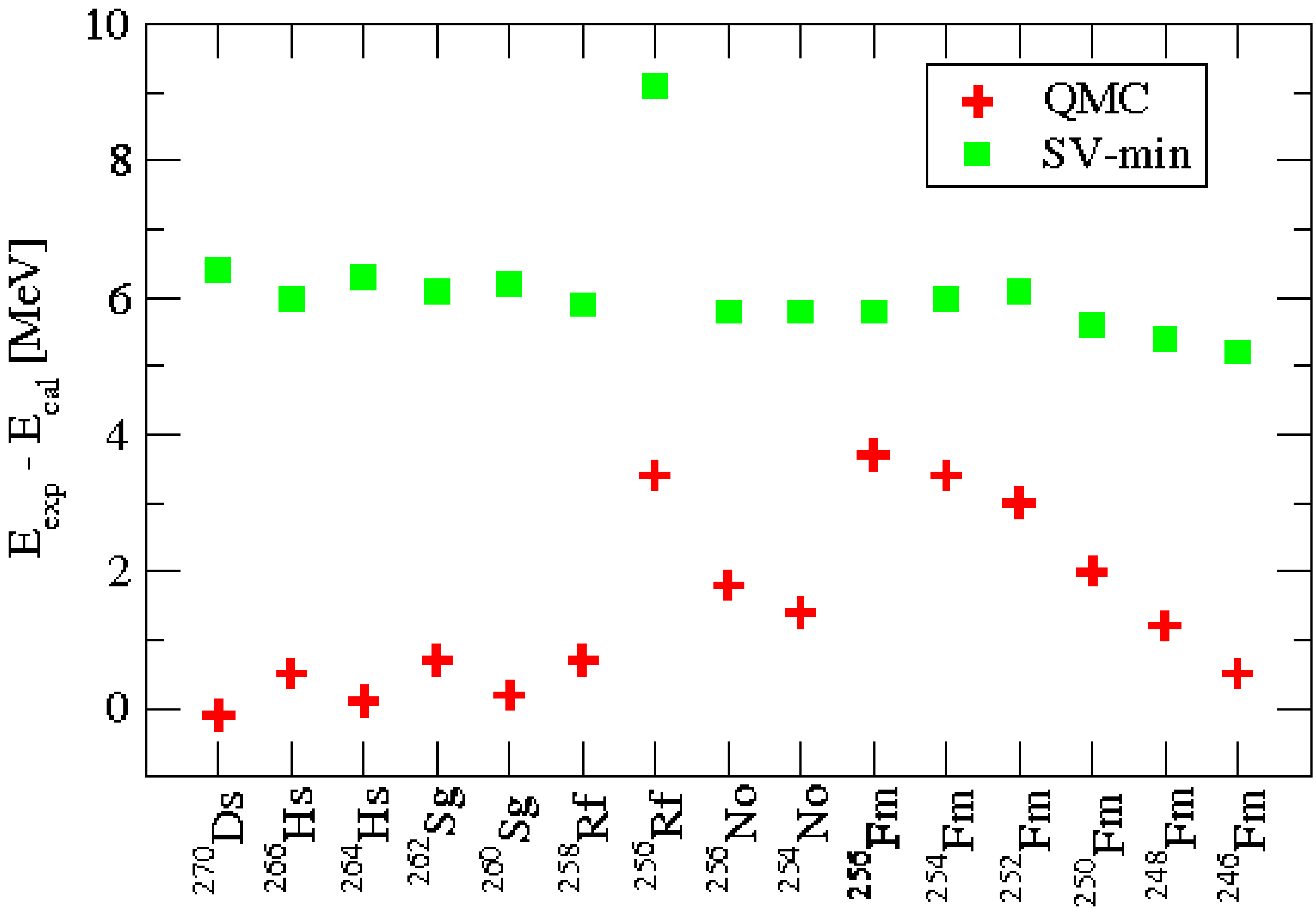
Element	Z	N	Element	Z	N
C	6	6 -16	Pb	82	116 - 132
O	8	4 -20	Pu	94	134 - 154
Ca	20	16 – 32	Fm	100	148 - 156
Ni	28	24 – 50	No	102	152 - 154
Sr	38	36 – 64	Rf	104	152 - 154
Zr	40	44 -64	Sg	106	154 - 156
Sn	50	50 – 86	Hs	108	156 - 158
Sm	62	74 – 98	Ds	110	160
Gd	64	74 -100			

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

Superheavy Binding : 0.1% accuracy



Stone et al., PRL 116 (2016) 092501

For detailed study of SHE see: arXiv:1901.06064

Giant Monopole Resonances

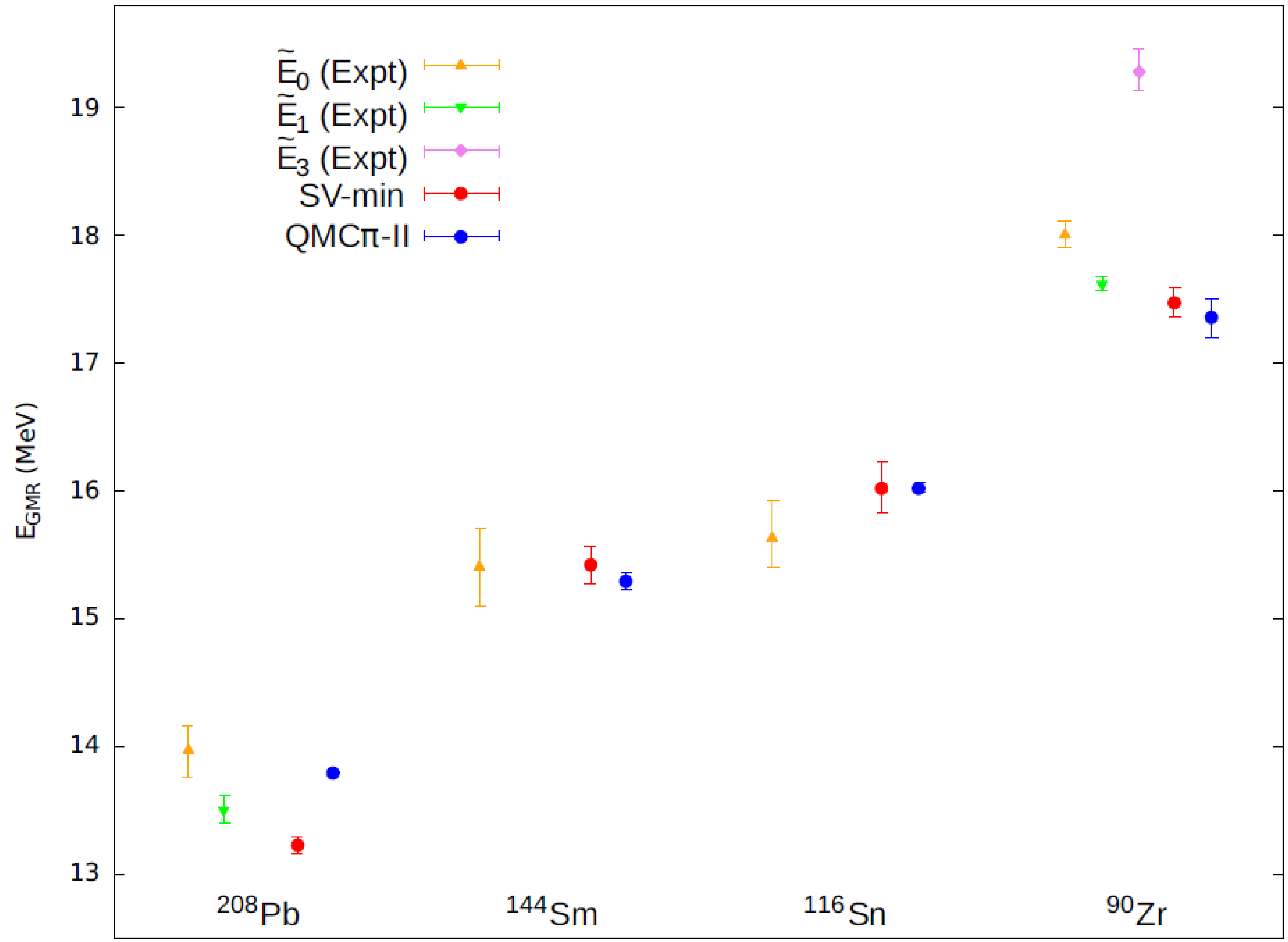


FIG. 13. GMR energies for ^{208}Pb, ^{144}Sm, ^{116}Sn, and ^{90}Zr from experiment and for the QMCπ-II and SVmin models. Experimental data are taken from Table 1 of Ref. [24].

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

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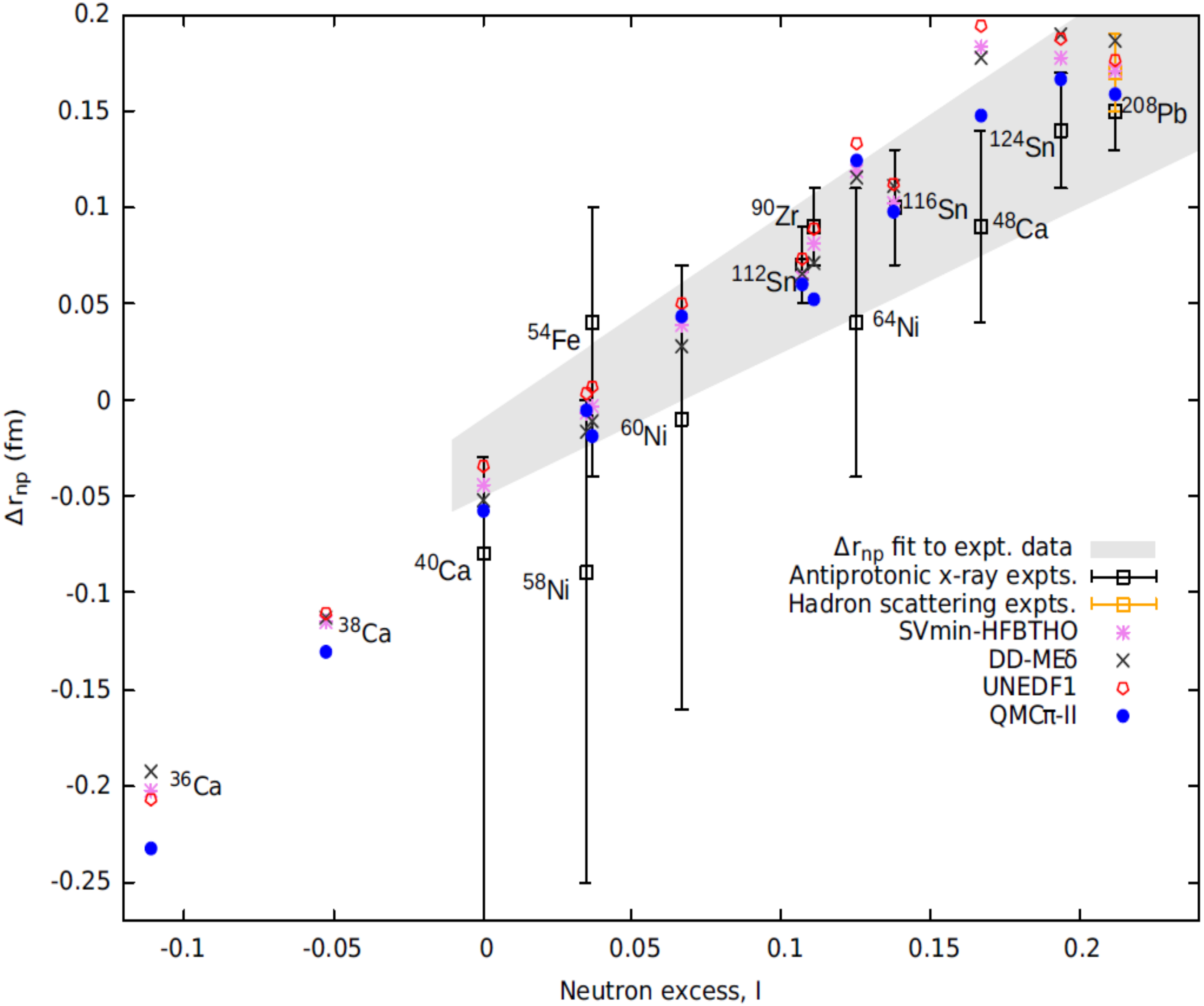
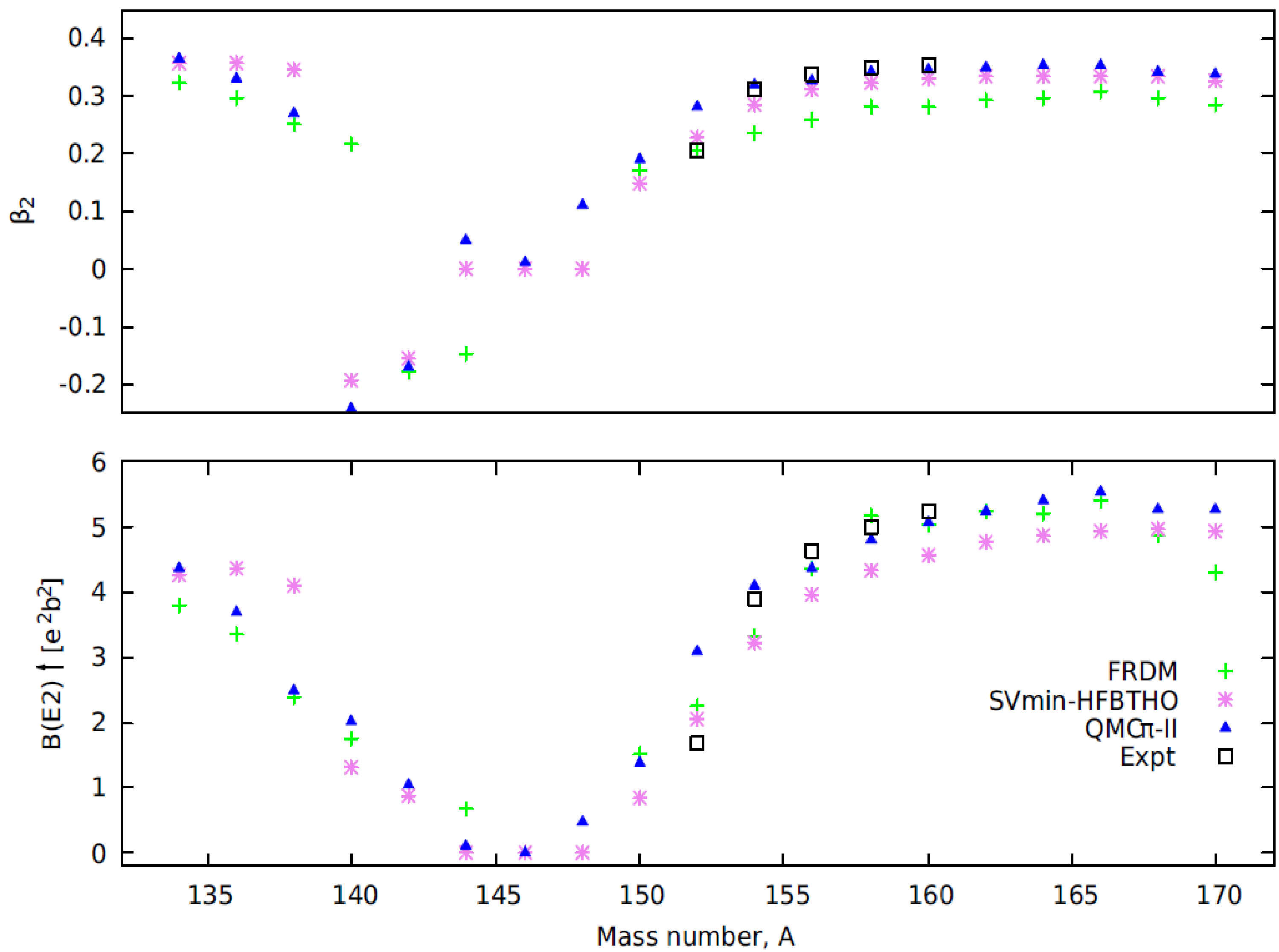
Neutron distributions



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

Deformation of Gd isotopes



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

Summary: Finite Nuclei

- The effective force was *derived* at the quark level *based upon the changing structure of a 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......

Nuclear DIS Structure Functions: The EMC Effect

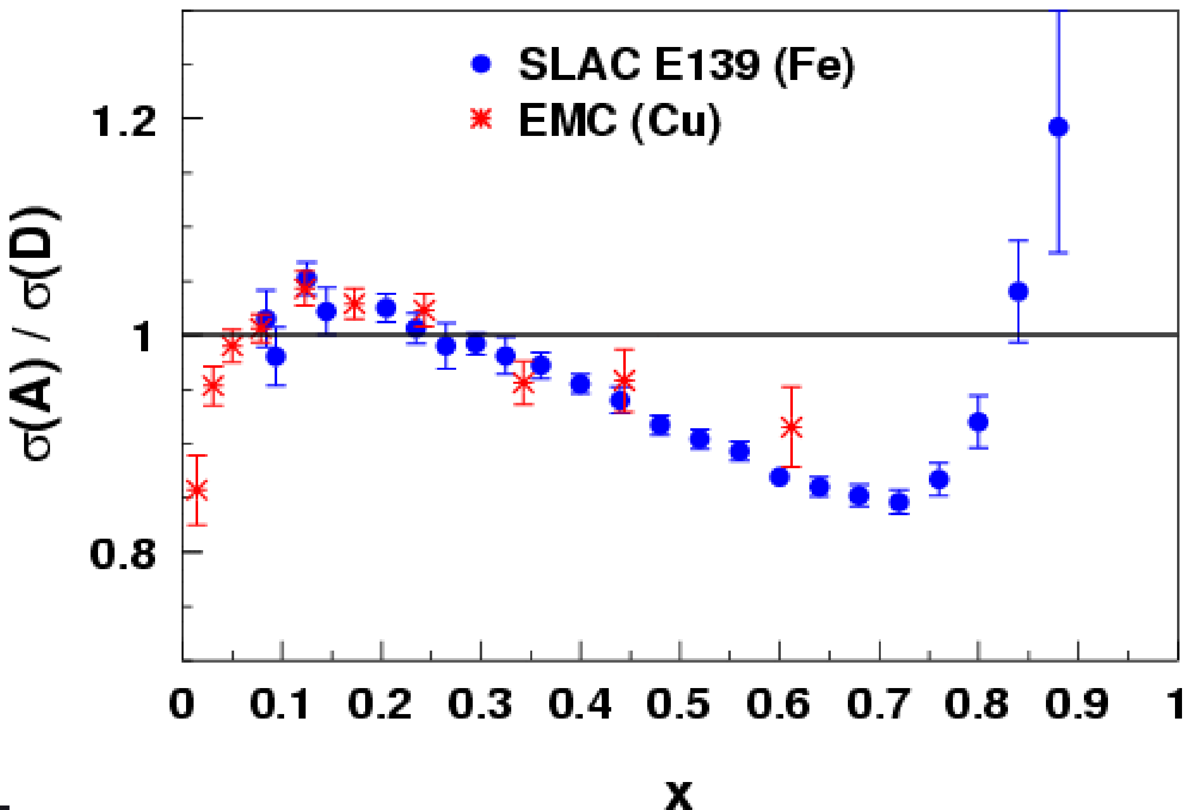
To address questions like this one MUST start with a theory that quantitatively describes nuclear structure and allows calculation of structure functions

– very, very few examples.....

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)

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)

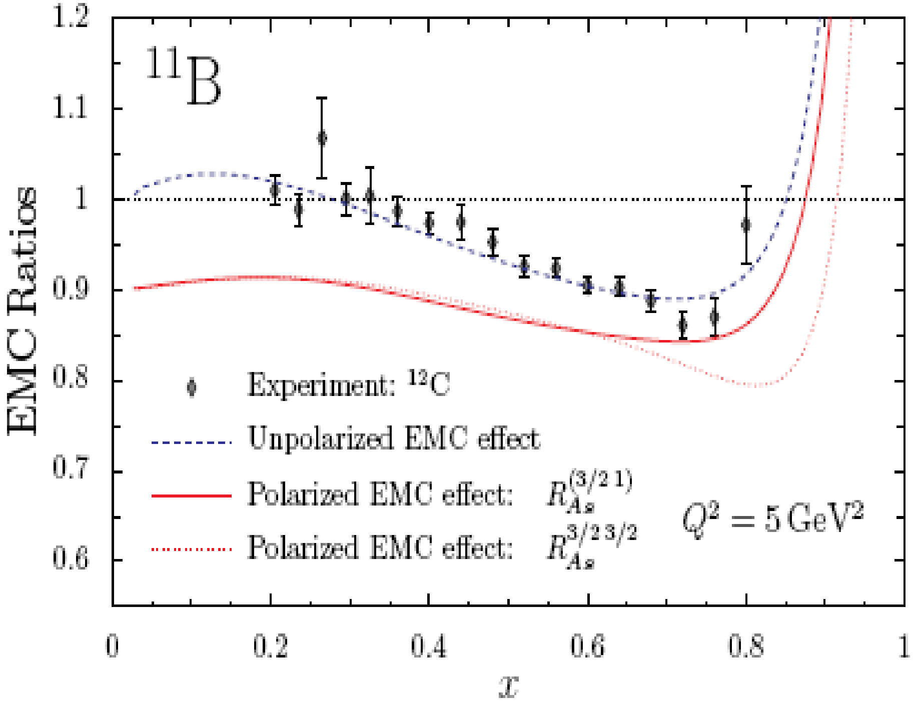


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

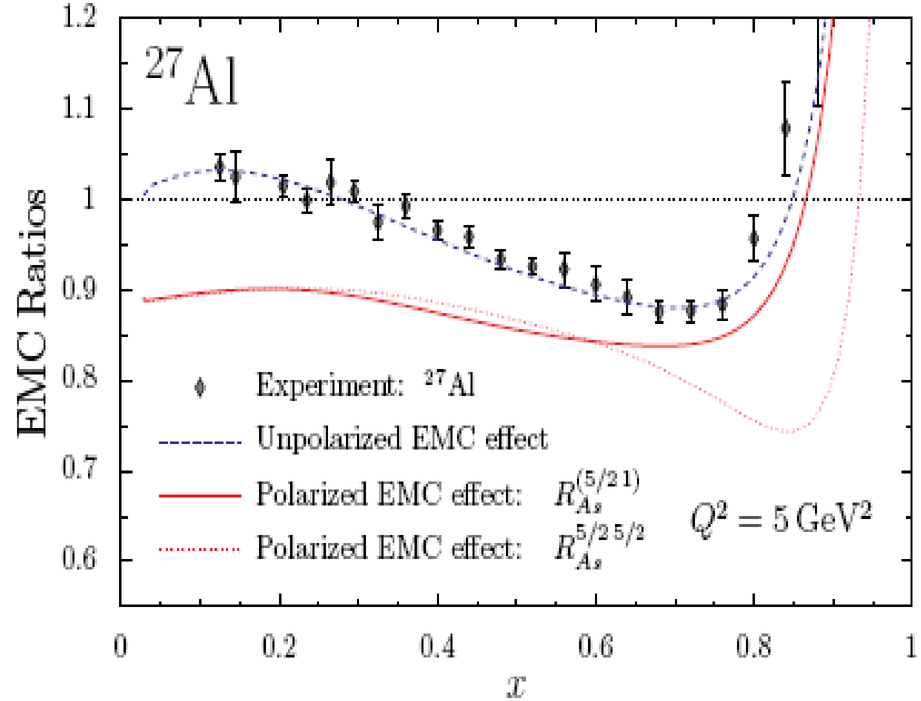
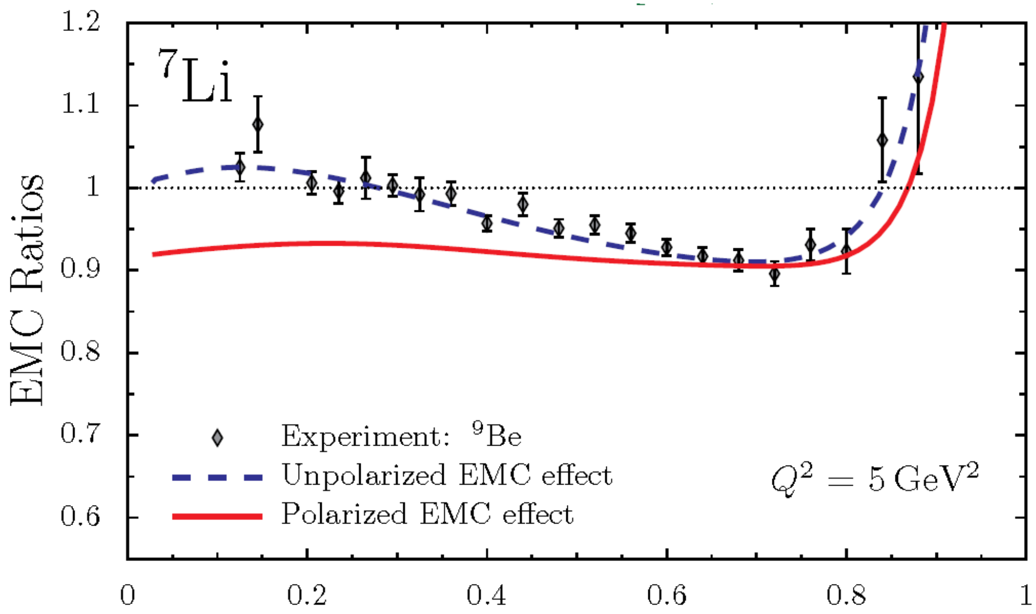


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

Cloët, Bentz &Thomas, Phys. Lett. B642 (2006) 210
Related work by Miller and co-workers

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: $P_p = 0.86$ & $P_n = 0.04$)



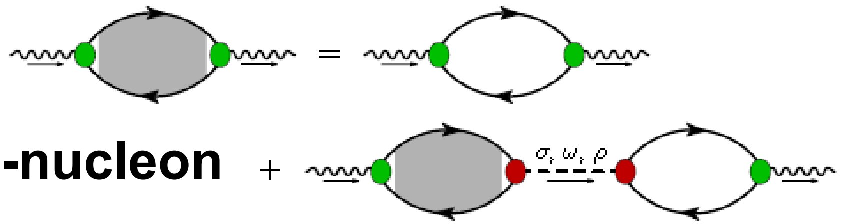
Spin EMC measurement is critical as the proposed explanation in terms of SRC through the tensor force gives NO spin EMC effect (arXiv:1809.06622)

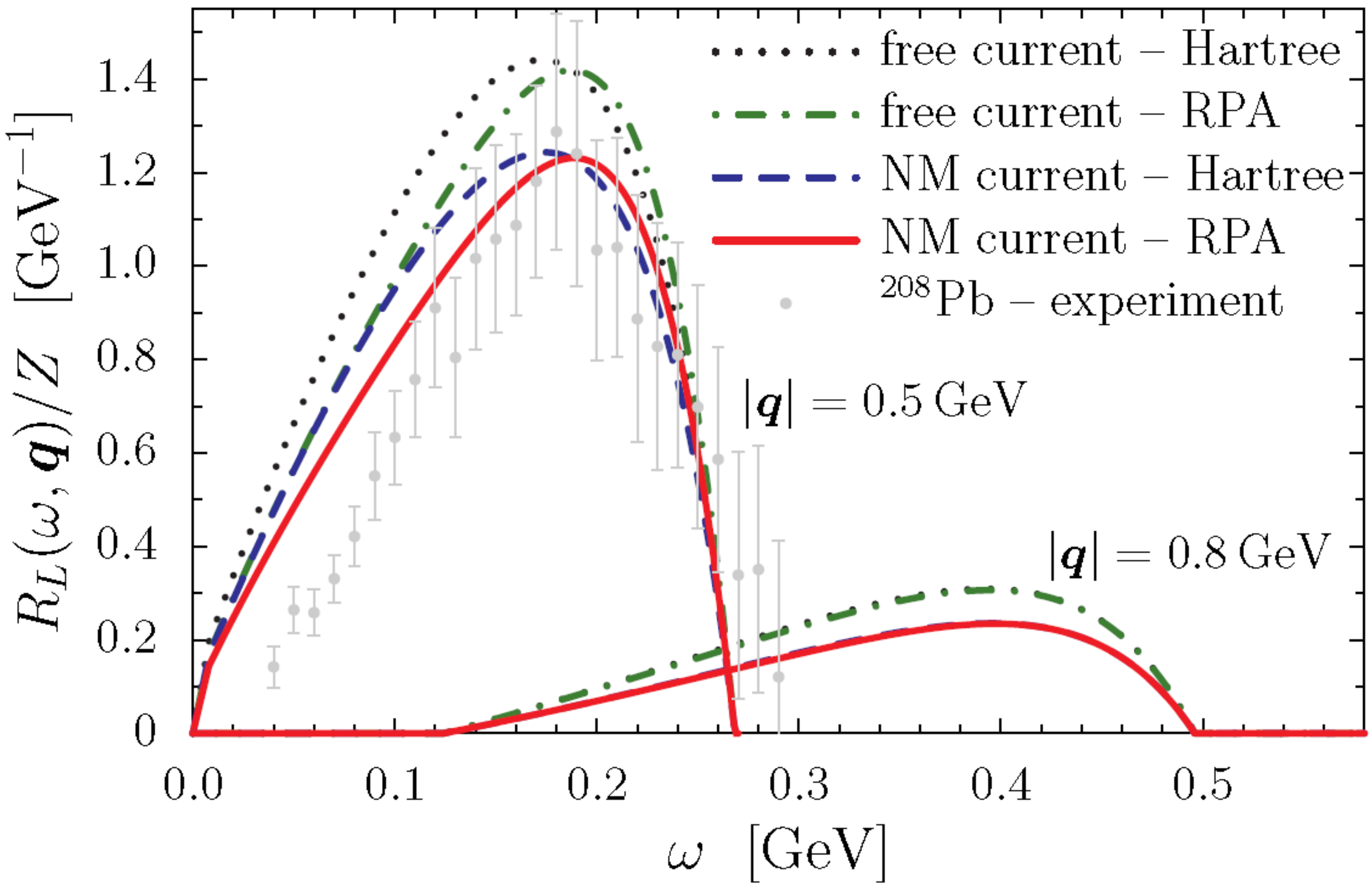
Modified Electromagnetic Form Factors In-Medium

Response Function

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

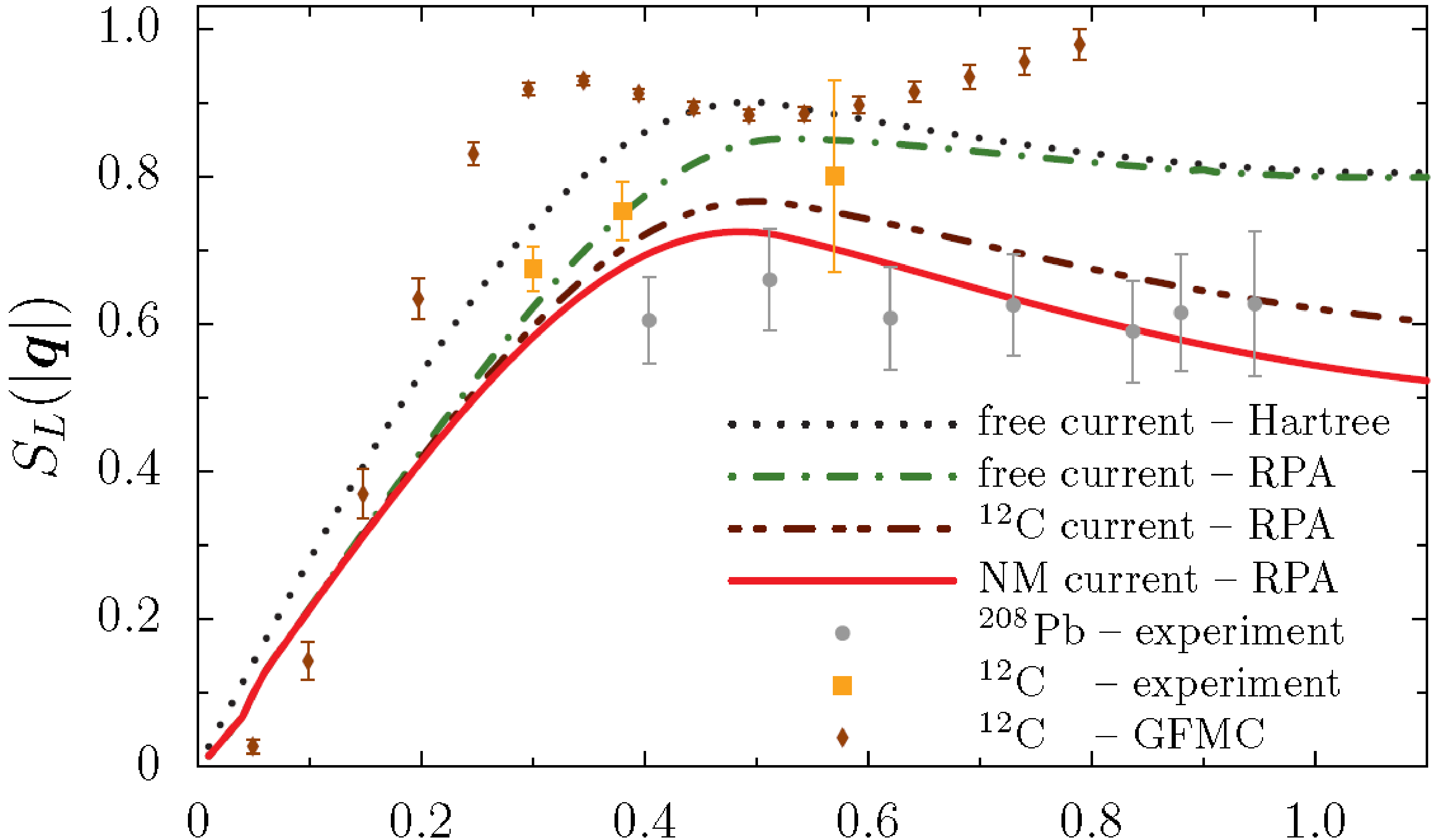
RPA correlations repulsive
Significant reduction in Response Function from the modification of bound-nucleon





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)

More Nuclear Structure

All results for QMC-III from
PhD thesis of Kay Martinez
- now at Silliman University (Philippines)
(publications in preparation)

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QMC π3

- **Just 5 parameters***: m_σ, quark couplings to σ, ω and ρ and λ_3 - the strength of σ^3 term

- Tensor term included:

$$H^J_{\sigma,\omega,\rho} = \left(\frac{G_\sigma(1-d\,\upsilon_0)^2}{4m_\sigma^2} - \frac{G_\omega}{4m_\omega^2}\right)\sum_m \vec{J}_m^2 - \frac{G_\rho}{4m_\rho^2}\sum_{m,m'} S_{m,m'}\vec{J}_m\cdot\vec{J}_{m'},$$

and

$$H^J_S = -\frac{G_\sigma - G_\omega}{16M^2}\sum_m \vec{J}_m^2 + \frac{G_\rho}{16M^2}\sum_{mm'} S_{m,m'}\vec{J}_m\cdot\vec{J}_{m'}.$$

with

$$\vec{J}_m = i\sum_{i\in F_m}\sum_{\sigma\sigma'}\vec{\sigma}_{\sigma'\sigma}\times[\vec{\nabla}\phi^i(\vec{r},\sigma,m)]\phi^{i*}(\vec{r},\sigma',m),\quad \vec{J} = \vec{J}_p + \vec{J}_n,$$

- Pairing interaction (simple BCS) derived in the model

$$V^{\rm QMC}_{\rm pair} = -\left(\frac{G_\sigma}{1+d'G_\sigma\rho(\vec{r})} - G_\omega - \frac{G_\rho}{4}\right)\delta(\vec{r}-\vec{r}\,')$$

*cf. Over 20 in FRDM and typically 16 (11+5) in Skyrme forces, although 7 in recent work of Bulgac *et al*.

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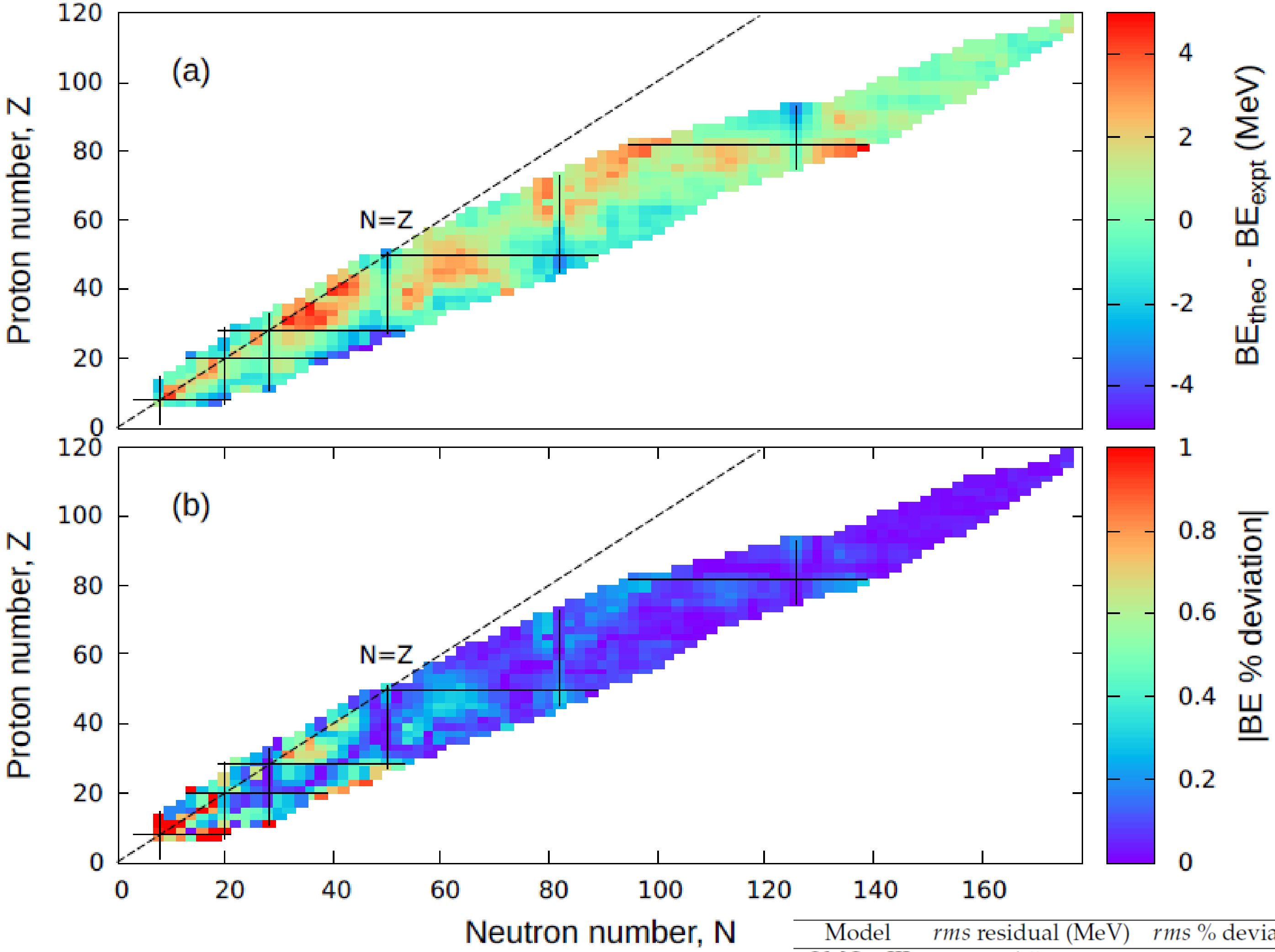
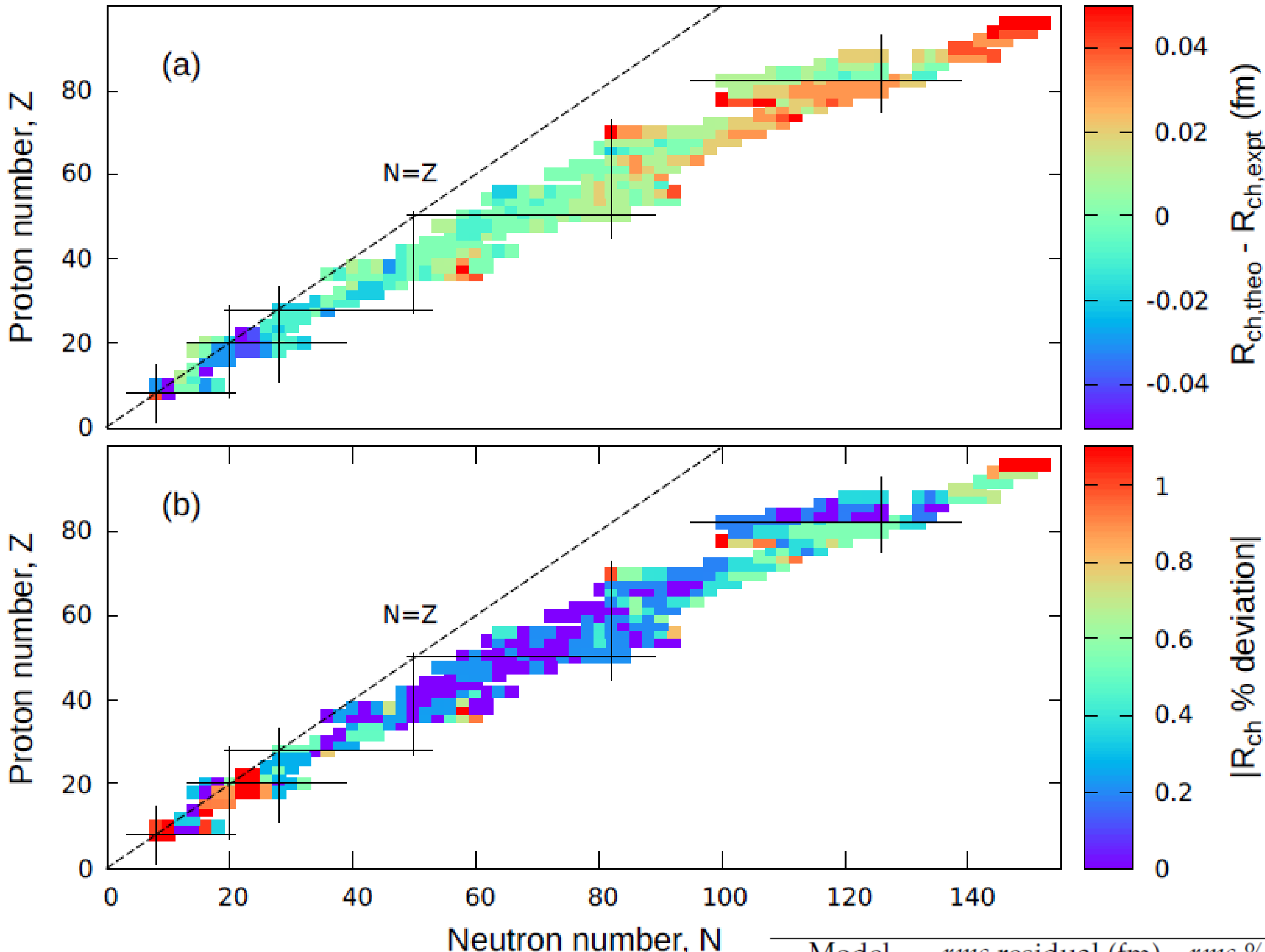
Binding Energies – All Known Even-Even Nuclei



Model	*rms* residual (MeV)	*rms* % deviation
QMCπ-III	1.59	0.29
QMCπ-II	2.34	0.39
QMCπ-I	2.78	0.50
QMC-I	3.84	0.69
SV-min	3.64	0.38
UNEDF1	2.06	0.55
DD-MEδ	2.41	0.42
FRDM	0.89	0.18

Charge Radii



Model	*rms* residual (fm)	*rms* % deviation
QMCπ-III	0.024	0.50
QMCπ-II	0.029	0.66
QMCπ-I	0.028	0.65
QMC-I	0.030	0.66
SV-min	0.024	0.61
UNEDF1	0.029	0.65
DD-MEδ	0.035	0.78

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Separation energies: Drip Lines

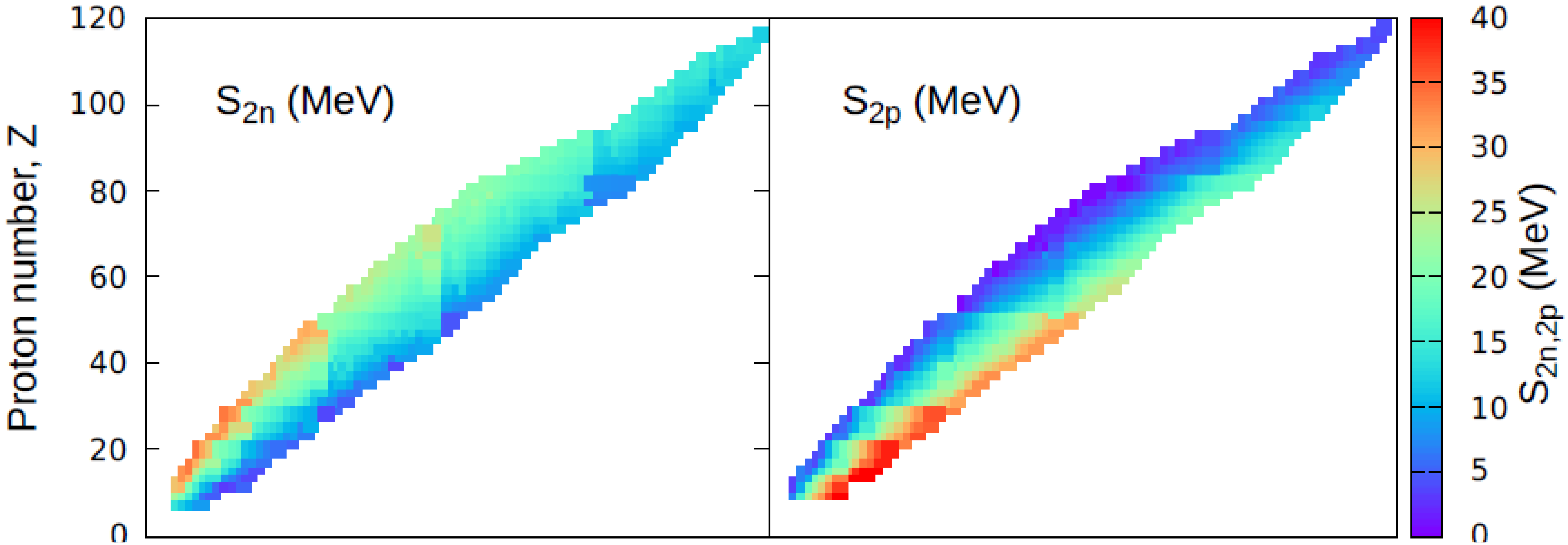

TABLE 7.3: Comparison of *rms* residuals for separation energies (in MeV) from QMC and from other nuclear models.

Model	S_{2n}	S_{2p}	δ_{2n}	δ_{2p}	Q_α
QMCπ-III	0.97	0.95	1.24	1.28	1.07
QMCπ-II	1.03	1.08	1.20	1.25	1.19
SV-min	0.77	0.82	0.87	1.00	0.79
UNEDF1	0.74	0.82	0.85	0.90	0.80
DD-MEδ	1.01	1.05	1.12	1.11	1.30
FRDM	0.50	0.55	0.61	0.75	0.61

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Deformation

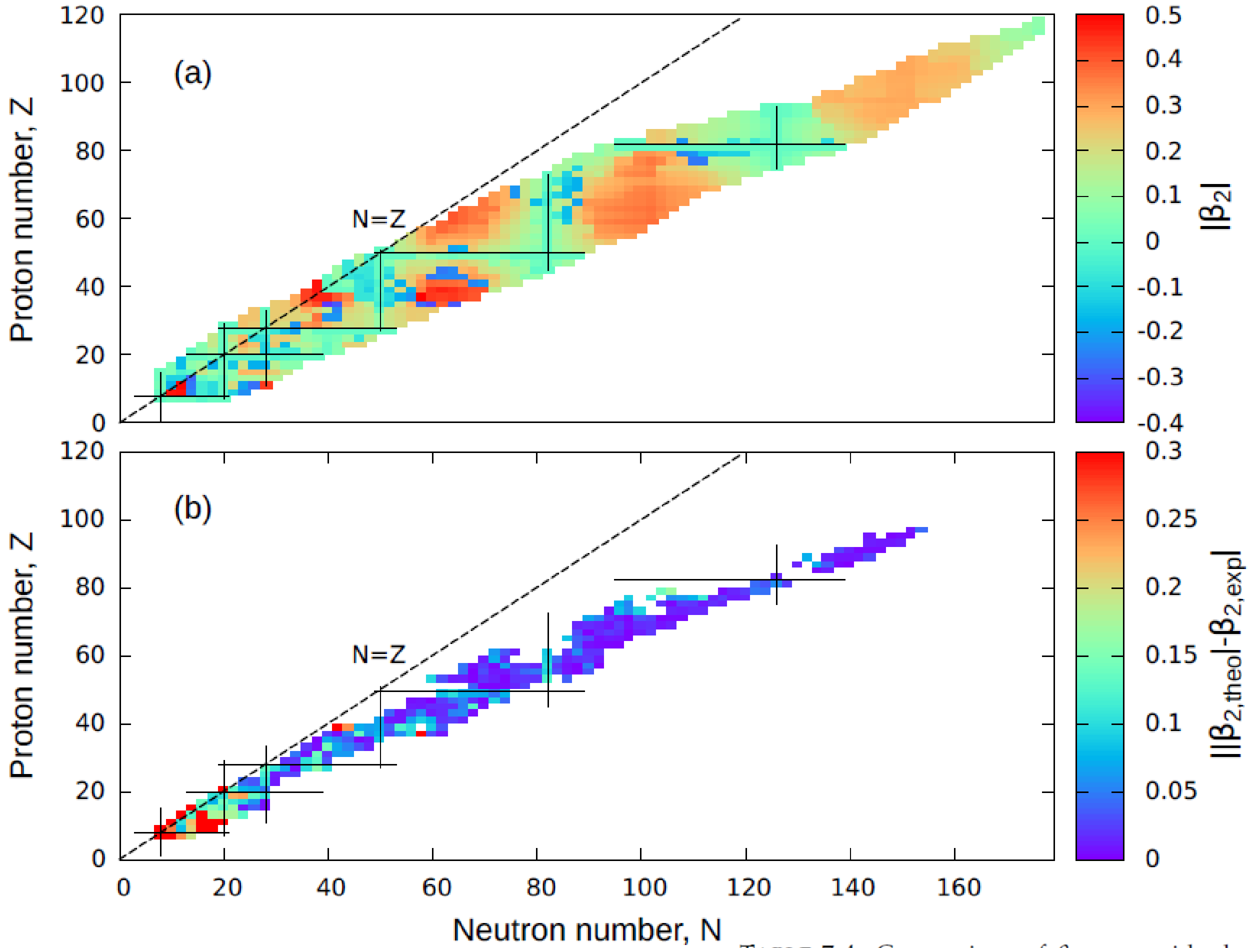

TABLE 7.4: Comparison of β_2 *rms* residuals and *rms* % deviations from QMCπ-III and from other nuclear models. There are a total of 324 even-even nuclei with available data for β_2 included for comparison.

Model	*rms* residual	*rms* % deviation
QMCπ-III	0.11	28
SV-min	0.16	59
UNEDF1	0.15	53
DD-MEδ	0.14	40
FRDM	0.11	30

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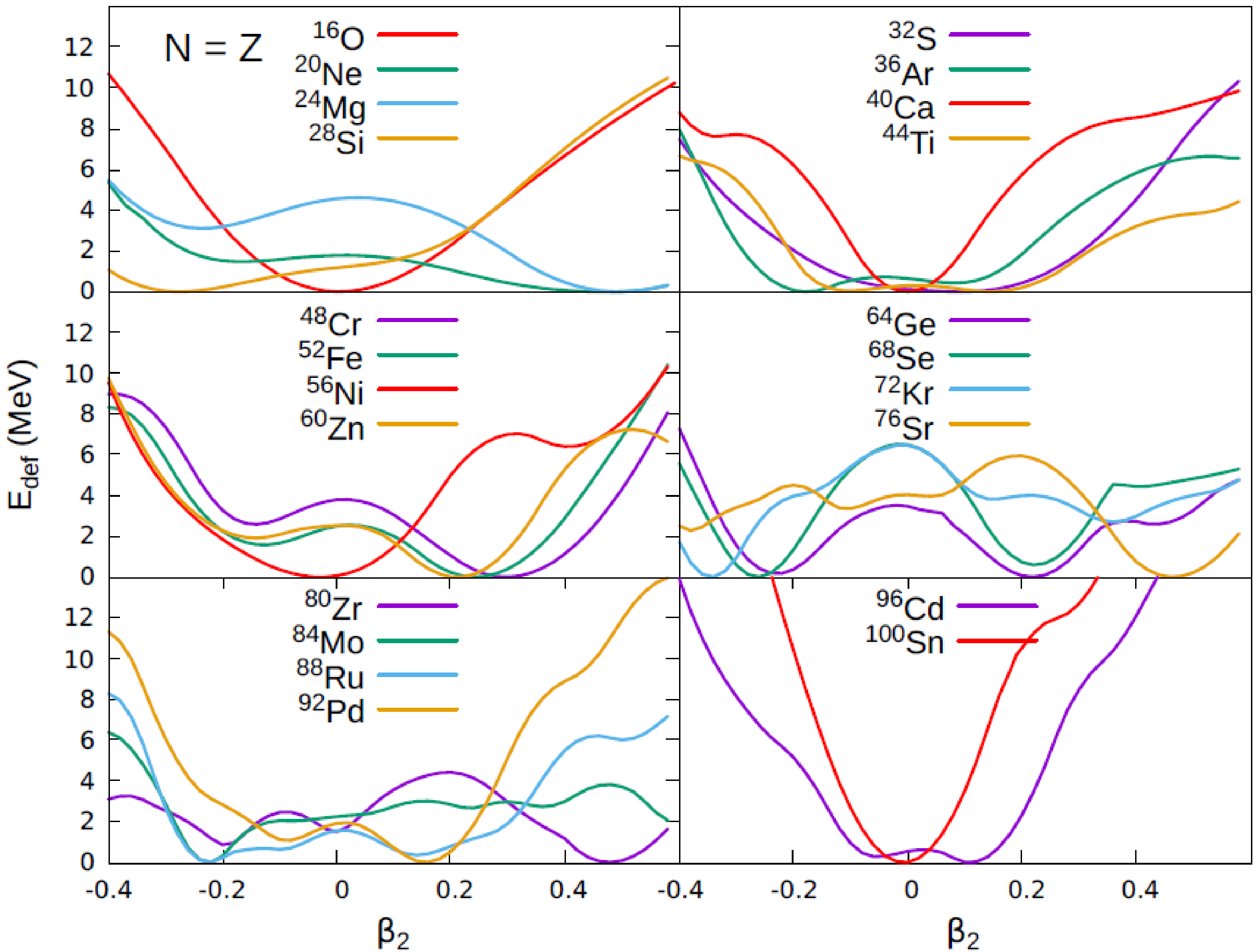
Shape Co-Existence for Z=N

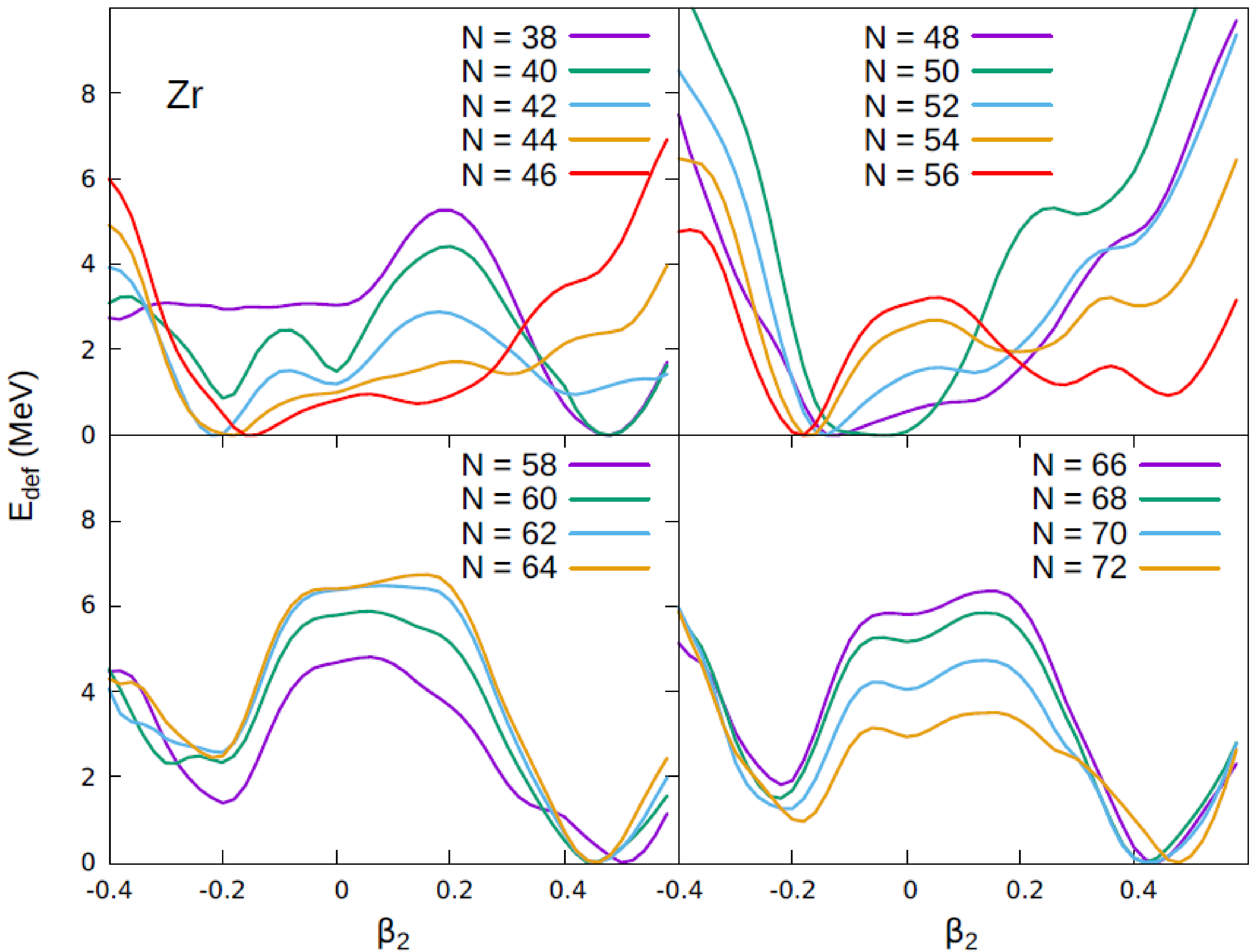


Shape Co-Existence

TABLE 7.5: β_2 values corresponding to the locations of the first and second deformed minima for symmetric nuclei obtained from QMCπ-III. Also added for comparison are experimental data which are only available in absolute values [52], as well as FRDM results [23].

Z or N	Expt.	QMCπ-III 1st	QMCπ-III 2nd	FRDM	Z or N	Expt.	QMCπ-III 1st	QMCπ-III 2nd	FRDM
8	0.36	0.00	-	-0.01	30	-	0.22	-0.14	0.16
10	0.73	0.46	-0.16	0.36	32	-	0.22	-0.22	0.21
12	0.61	0.50	-0.24	0.39	34	-	-0.26	0.22	0.23
14	0.41	-0.28	-	-0.36	36	-	-0.34	-	-0.37
16	0.31	0.10	-	0.22	38	-	0.46	-	0.40
18	0.26	-0.18	0.08	-0.26	40	-	0.48	-0.20	0.43
20	0.12	0.00	-	0.00	42	-	-0.22	-	-0.23
22	0.27	0.14	-	0.00	44	-	-0.22	0.14	-0.24
24	0.34	0.30	-0.14	0.23	46	-	0.16	-0.16	0.00
26	-	0.24	-0.12	0.12	48	-	0.10	-0.06	-0.02
28	0.17	-0.02	-	0.00	50	-	0.00	-	0.00

Shape Co-Existence: Z = 40



The Superheavy Region

First study:

PHYSICAL REVIEW C **100**, 044302 (2019)

Physics of even-even superheavy nuclei with $96 < Z < 110$ in the quark-meson-coupling model

J. R. Stone[*]
Department of Physics (Astro), University of Oxford, Keble Road OX1 3RH, Oxford, United Kingdom and Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA

K. Morita[†]
Department of Physics, Kyushu University, Nishi-ku, Fukuoka 819-0395, Japan and RIKEN Nishina Center, RIKEN, Wako-shi, Saitama 351-0198, Japan

P. A. M. Guichon[‡]
CEA/IRFU/SPhN Saclay, F91191, France

A. W. Thomas[§]
CSSM and CoEPP, Department of Physics, University of Adelaide, SA 5005, Australia

Updated and expanded here (Martinez thesis)

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Binding Energies

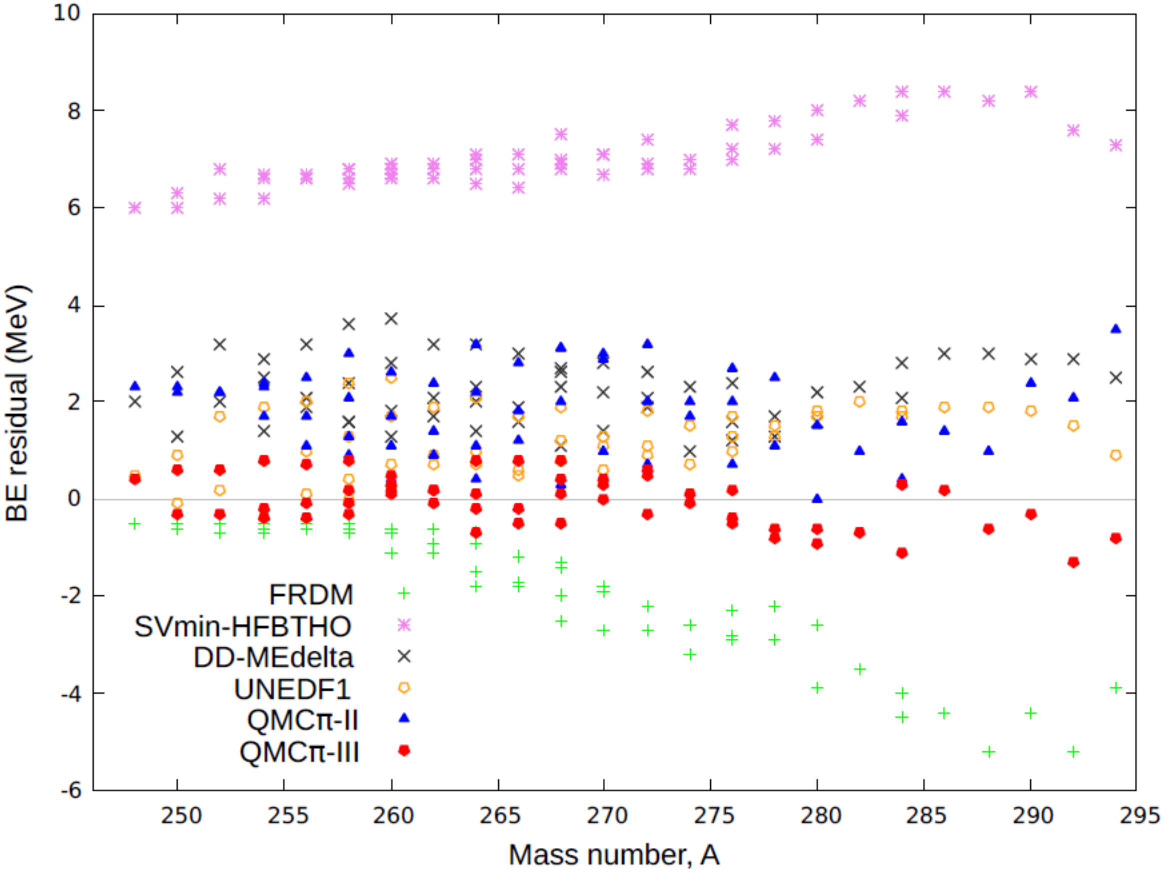
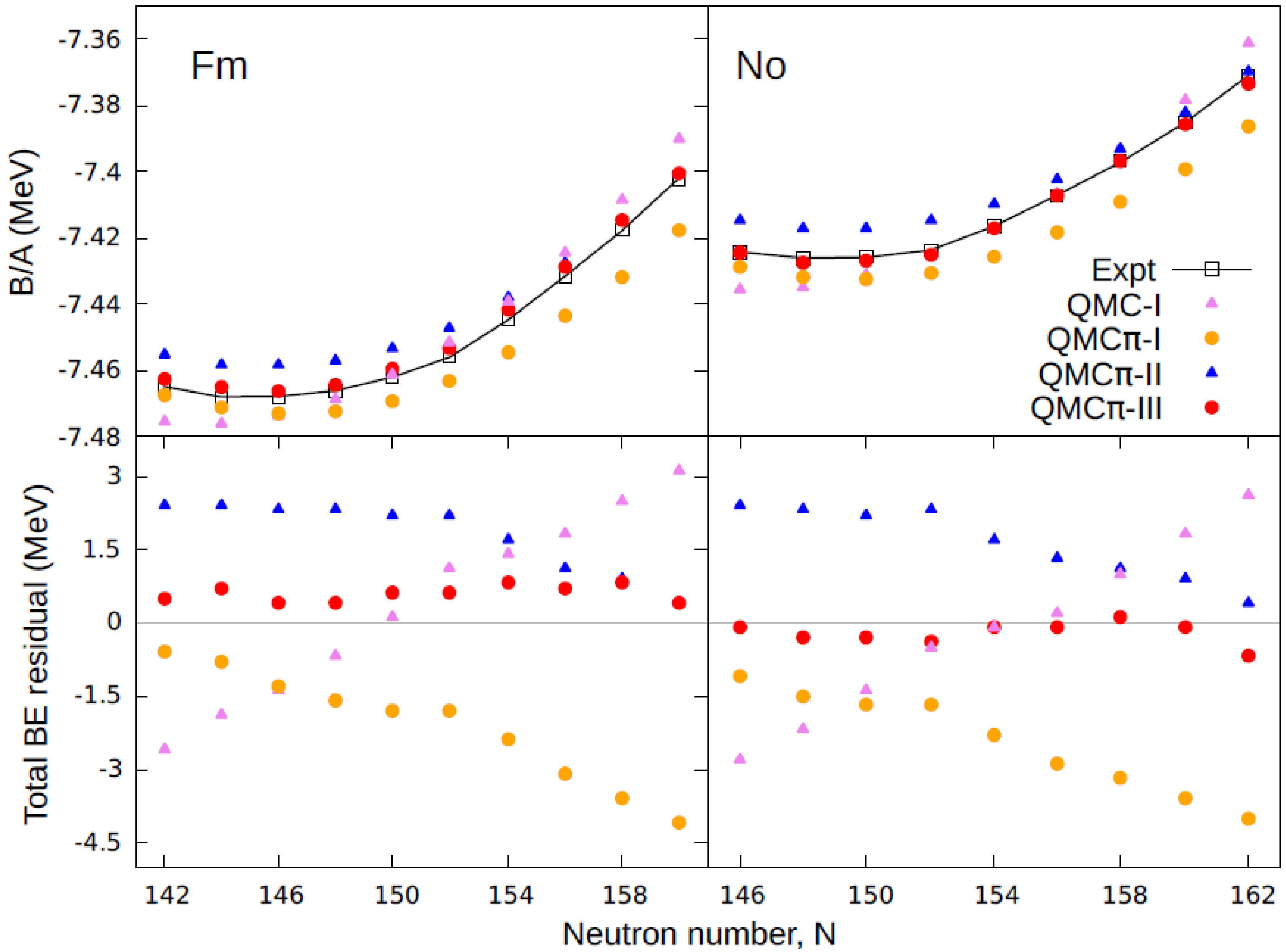


TABLE 6.1: Comparison of *rms* percent deviations and *rms* residuals from QMC and from other nuclear models for SHE with available data.

	rms % deviation	*rms* residual (MeV)
QMCπ-III	0.03	0.52
QMCπ-II [54]	0.11	2.04
QMCπ-I [53]	0.12	2.42
QMC-I [8]	0.08	1.50
FRDM [23]	0.11	2.25
SV-min [24]	0.36	6.99
UNEDF1 [28]	0.07	1.31
DD-MEδ [66]	0.12	2.28

Outstanding agreement

Trends Along Chains: ^{100} Fermium and ^{102} Nobelium



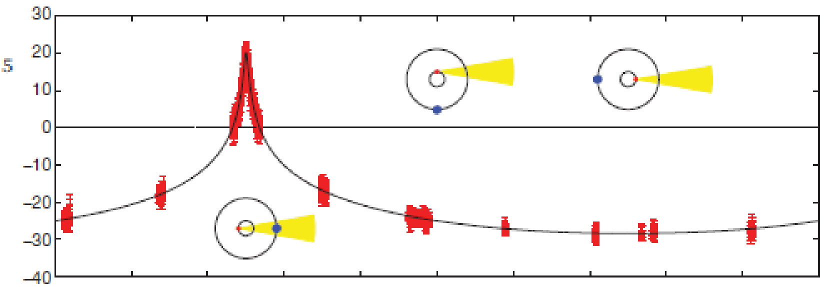
Neutron Stars

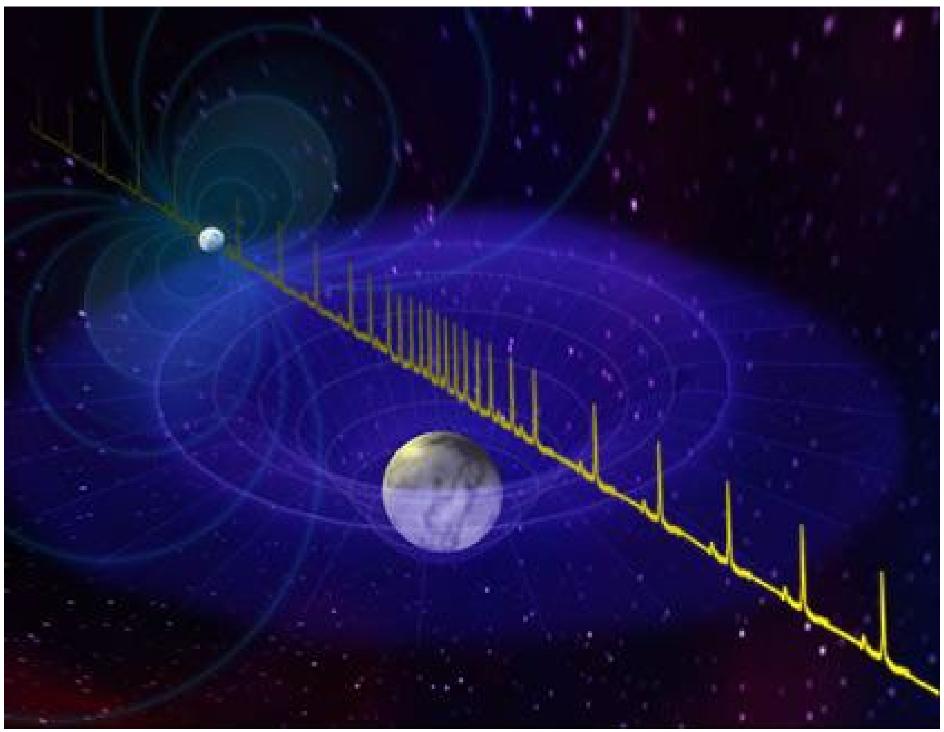
LETTER (2010)

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

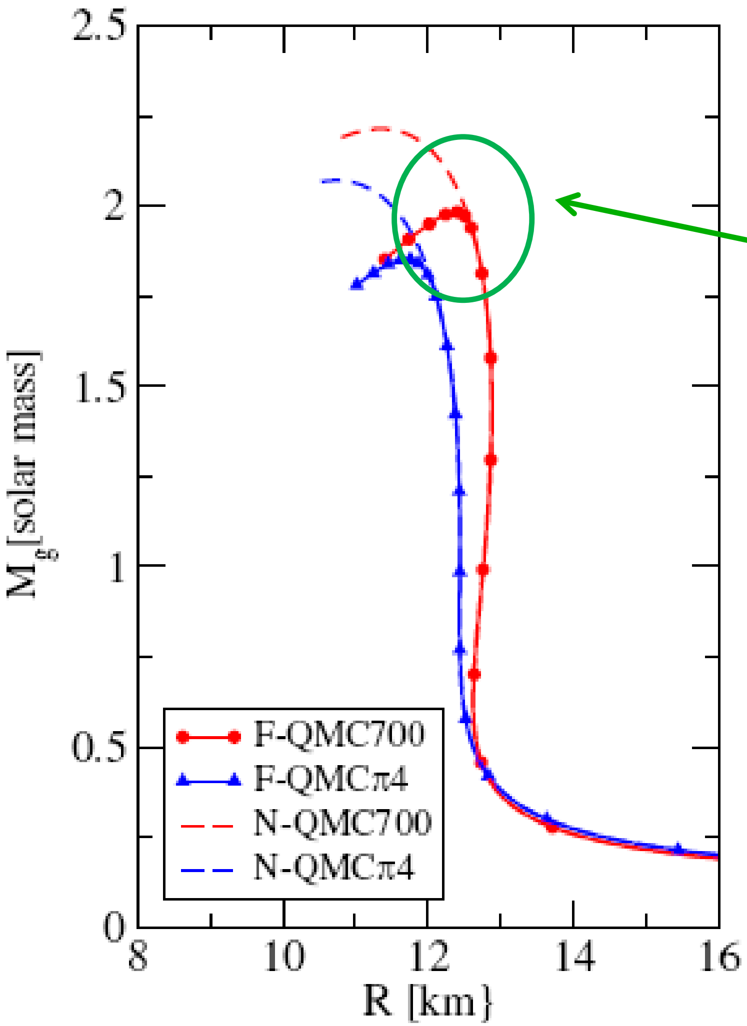
Claim: it rules out hyperon occurrence

- ignored our work *published* three years before!

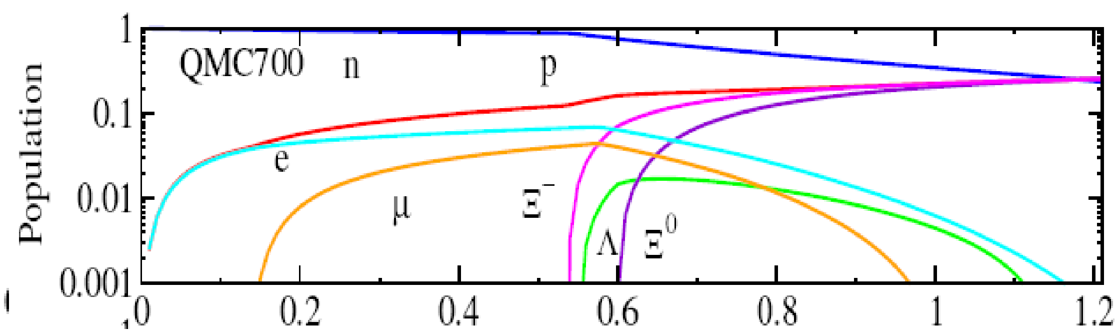
J1614-2230

Consequences of QMC for Neutron Star

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

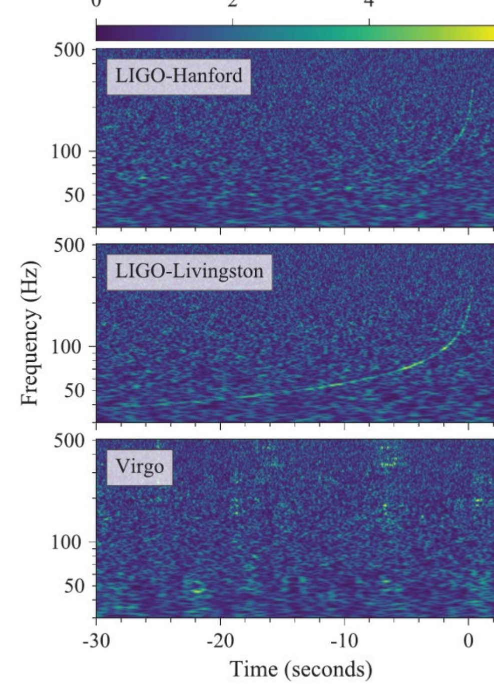


2 Solar mass stars predicted with hyperons present:



<u>Predicted</u> HNN forces were crucial!

Later work: Saito et al., Whittenbury et al.....



GW170817: Measurements of neutron star radii and equation of state

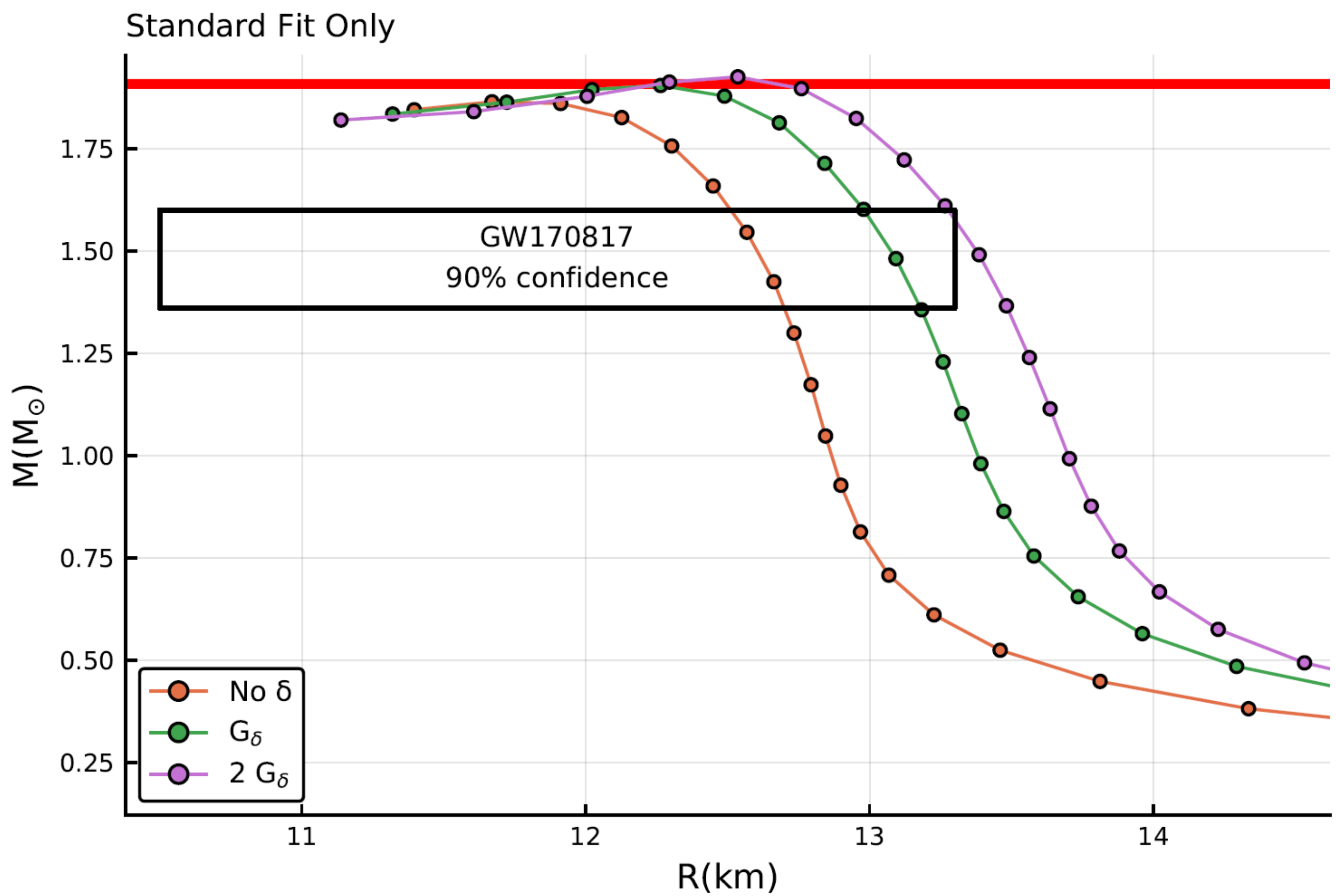
The LIGO Scientific Collaboration and The Virgo Collaboration
(compiled 30 May 2018)

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

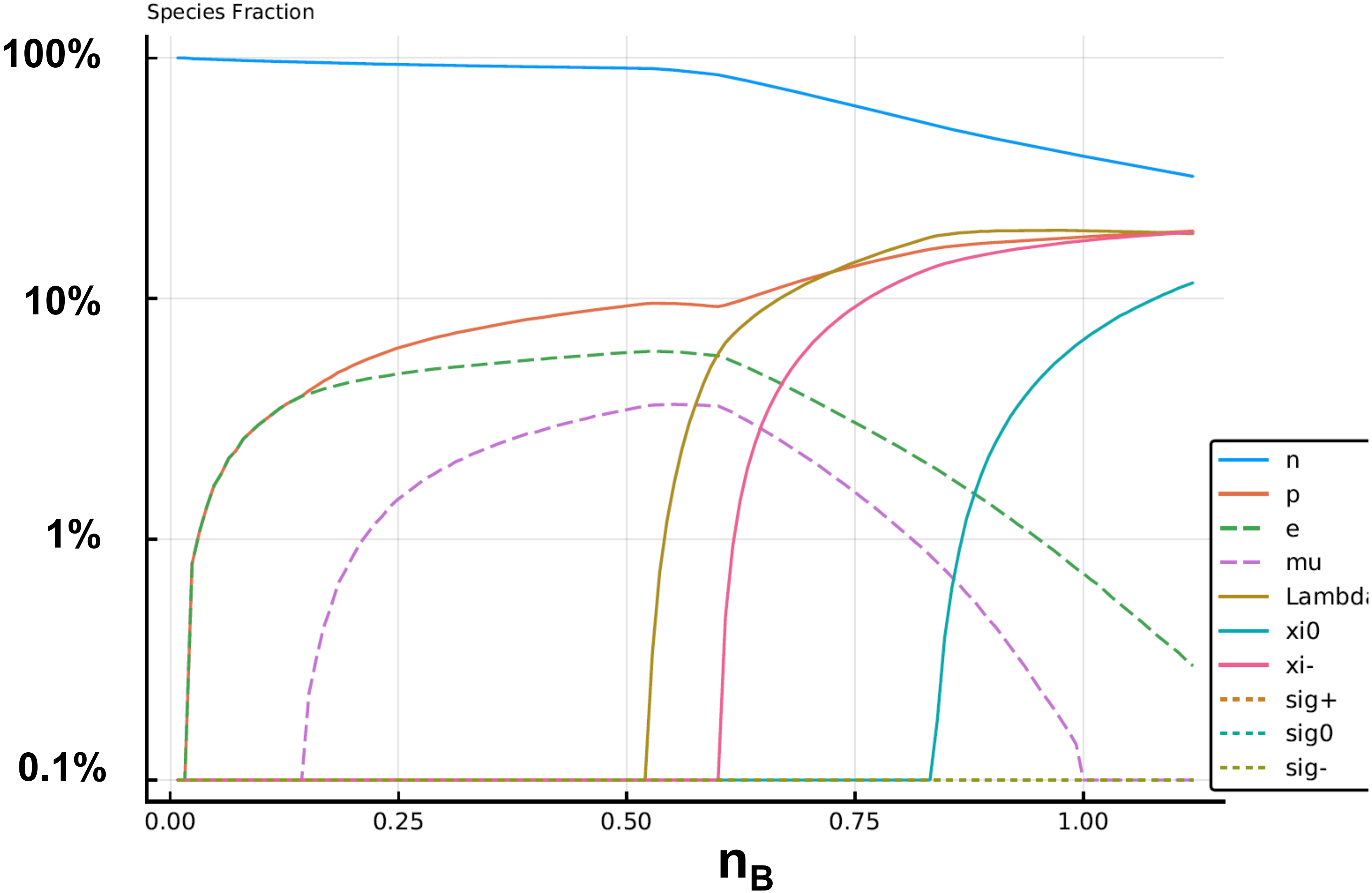
Recent Study Motivated by GW170817

- **Includes isovector scalar meson**



Motta, Kalaitzis *et al*., Ap J 878 (2019) 159

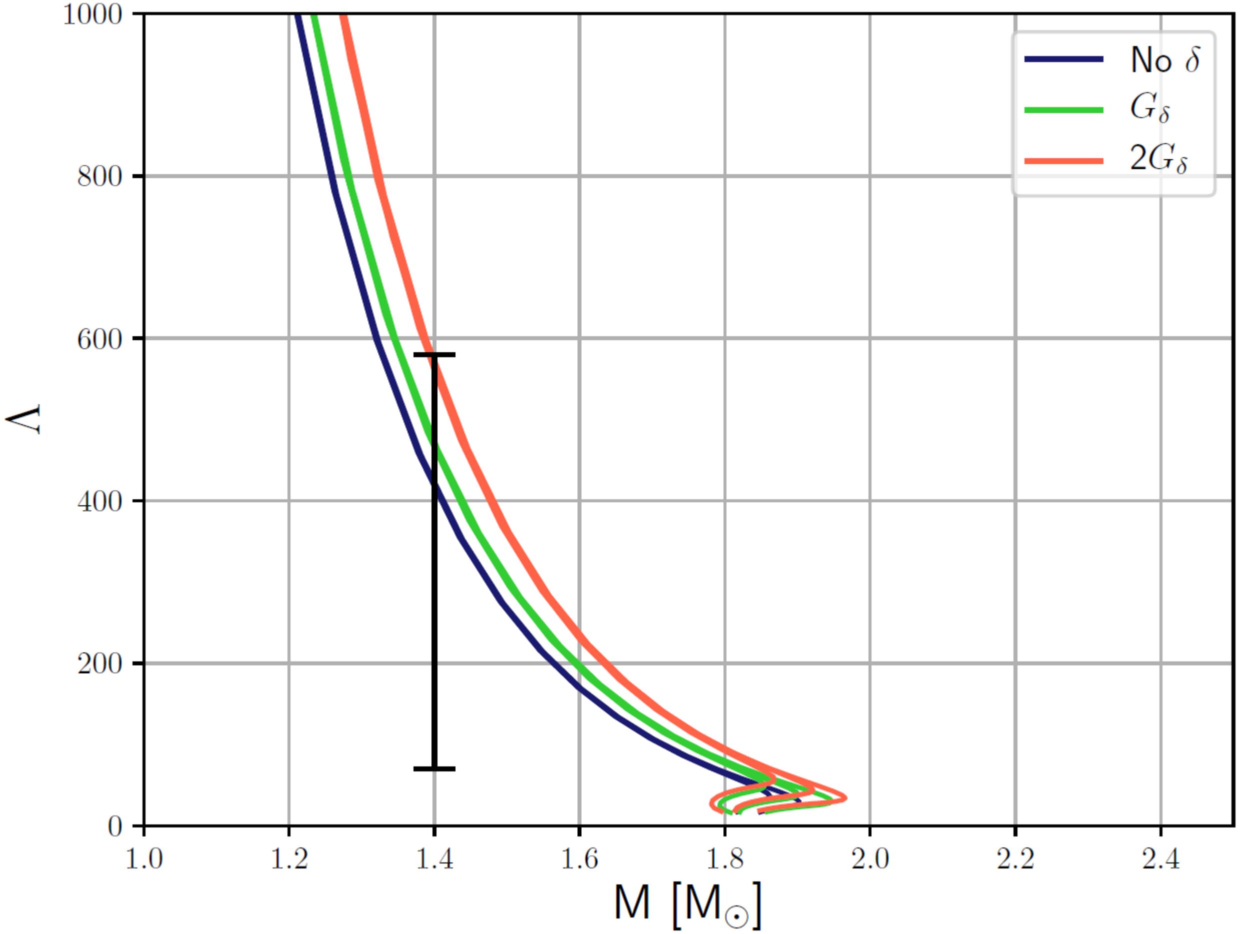
Species Fractions: in β-equilibrium

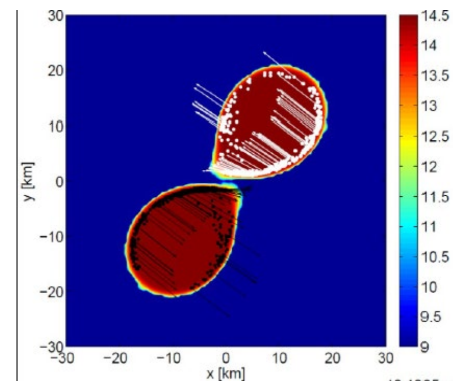


Motta, Kalaitzis *et al.*, Ap J 878 (2019) 159

Tidal deformability

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





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

Motta, Kalaitzis *et al.*, Ap J 878 (2019) 159

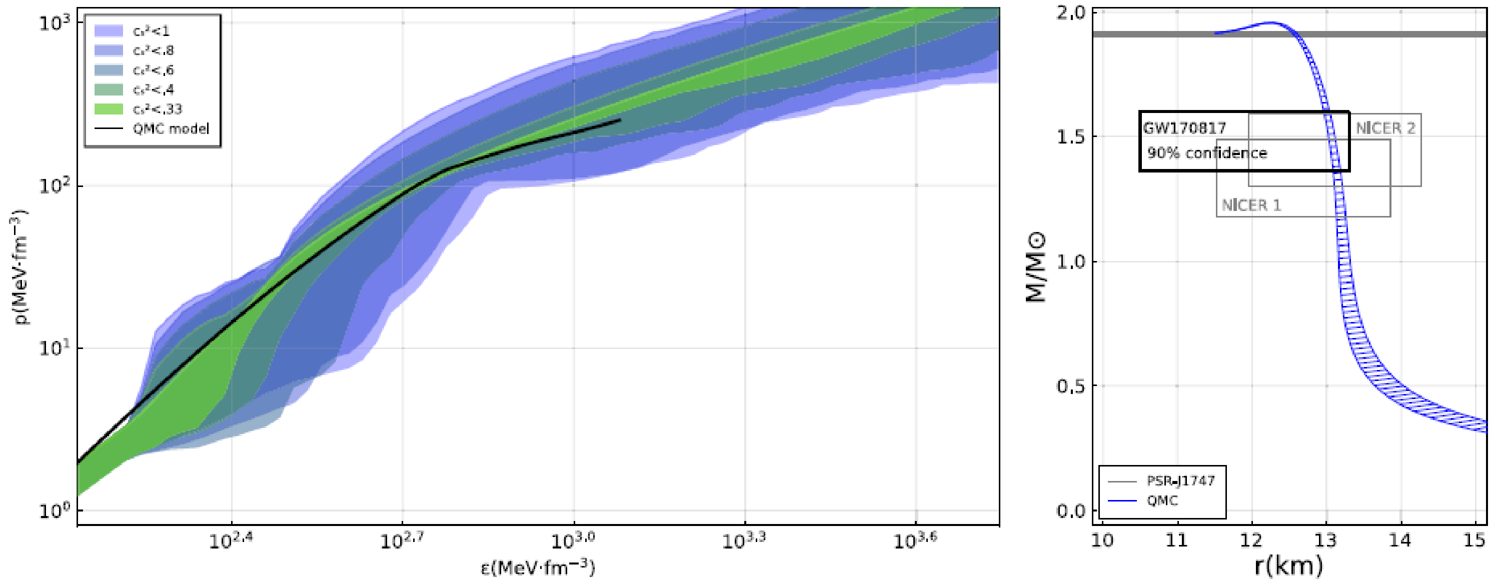
ELSEVIER

Nuclear Physics A 1009 (2021) 122157

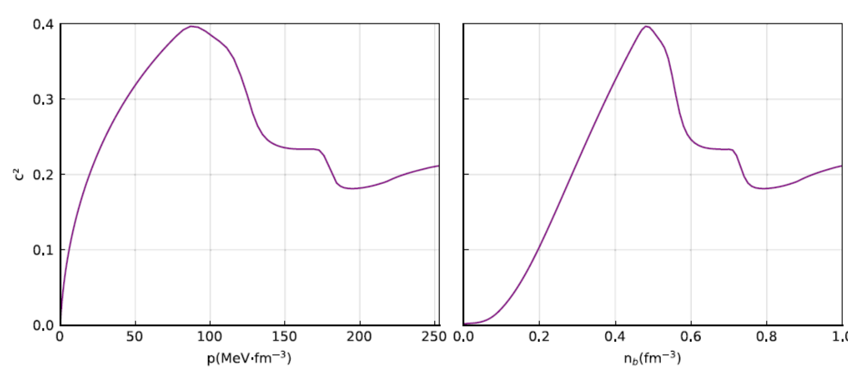
www.elsevier.com/locate/nuclphysa

On the sound speed in hyperonic stars

T.F. Motta [a,*], P.A.M. Guichon [b], A.W. Thomas [a]



Follow up on Annala et al., Nature Physics (2020) model independent EoS based on speed of sound interpolation between low and high density
- claim low value implies quark matter



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DARK MATTER

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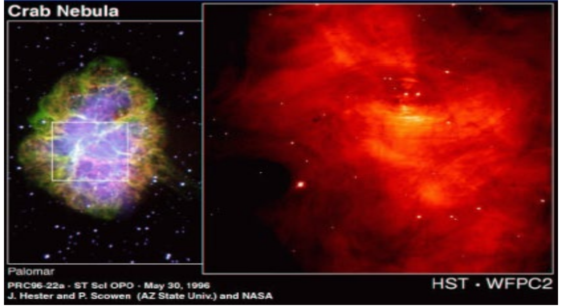
I. Summary



- 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

II. Summary

- Yields neutron stars at $2M_{\odot}$ *with hyperons*
  - Consistent with the tidal deformability deduced from GW170817 and NICER data

- Need empirical confirmation:
  - Response Functions & Coulomb sum rule (soon?)
  - EMC effect; spin EMC (not too long?)

- Initial systematic study of finite nuclei very promising

  With just 5 parameters:
  - Binding energies typically within 0.29% across periodic table
  - Super-heavies (Z > 100) especially good: 0.03%
  - Systematics of charge radii, deformations, shell and subshell closures pretty good

Special Mentions……


Guichon

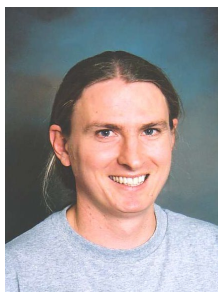

Tsushima


Saito


Stone


Krein


Matevosyan


Cloët


Whittenbury


Simenel


Bentz


Martinez


Motta


Antic


Kalaitzis

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Latest papers

- **QMC π3;**
  Martinez et al., Phys Rev C102 (2020) 034304

- **Review:**
  Guichon *et al.*, PPNP 100 (2018) 262

- **SHE:**
  Stone *et al.*, arXiv: 1901.06064

- **Systematic application to finite nuclei:**
  Stone *et al.*, Phys Rev Lett 116 (2016) 092501

Key papers on QMC

- **Many-body forces:**
  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)
  6. Guichon et al., Prog. Part. Nucl. Phys. 100 (2018) 262

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