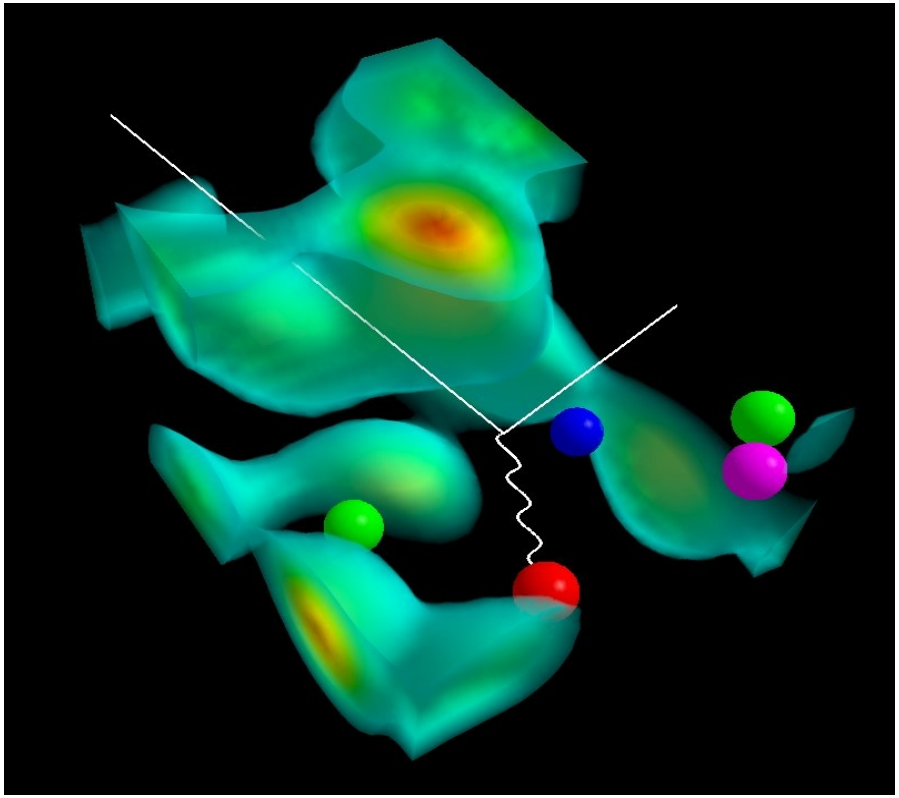
Origins of Nuclear Structure in QCD



CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Anthony W. Thomas

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

ICNFP 2019
Kolymbari, Crete : 23rd August 2019

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
- EMC effect (including spin): only if questions raised

III. Neutron Stars
- role of hyperons and insights from GW170817

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**

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

What do we know?

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

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

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

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

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

Suggests a different approach : QMC Model

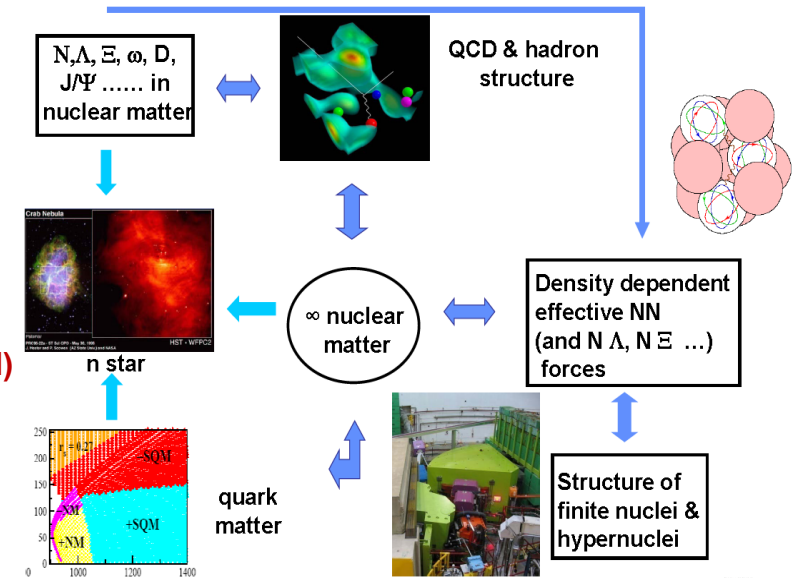
(Guichon, Saito, Tsushima et al., Rodionov et al.
- see Saito et al., Prog. Part. Nucl .Phys. 58 (2007) 1 and
Prog. Part. Nucl. Phys. 100 (2018) 262-297 for reviews)

- 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 only 3 parameters (4 if σ mass not fixed)

  – determine by fitting to:
    ρ_0 , E/A and symmetry energy
  – same in dense matter & finite nuclei



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

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.

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:**

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

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Derivation of EDF (cont.)

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

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

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

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

Spin-orbit force predicted!

Note the totally new, subtle density dependence

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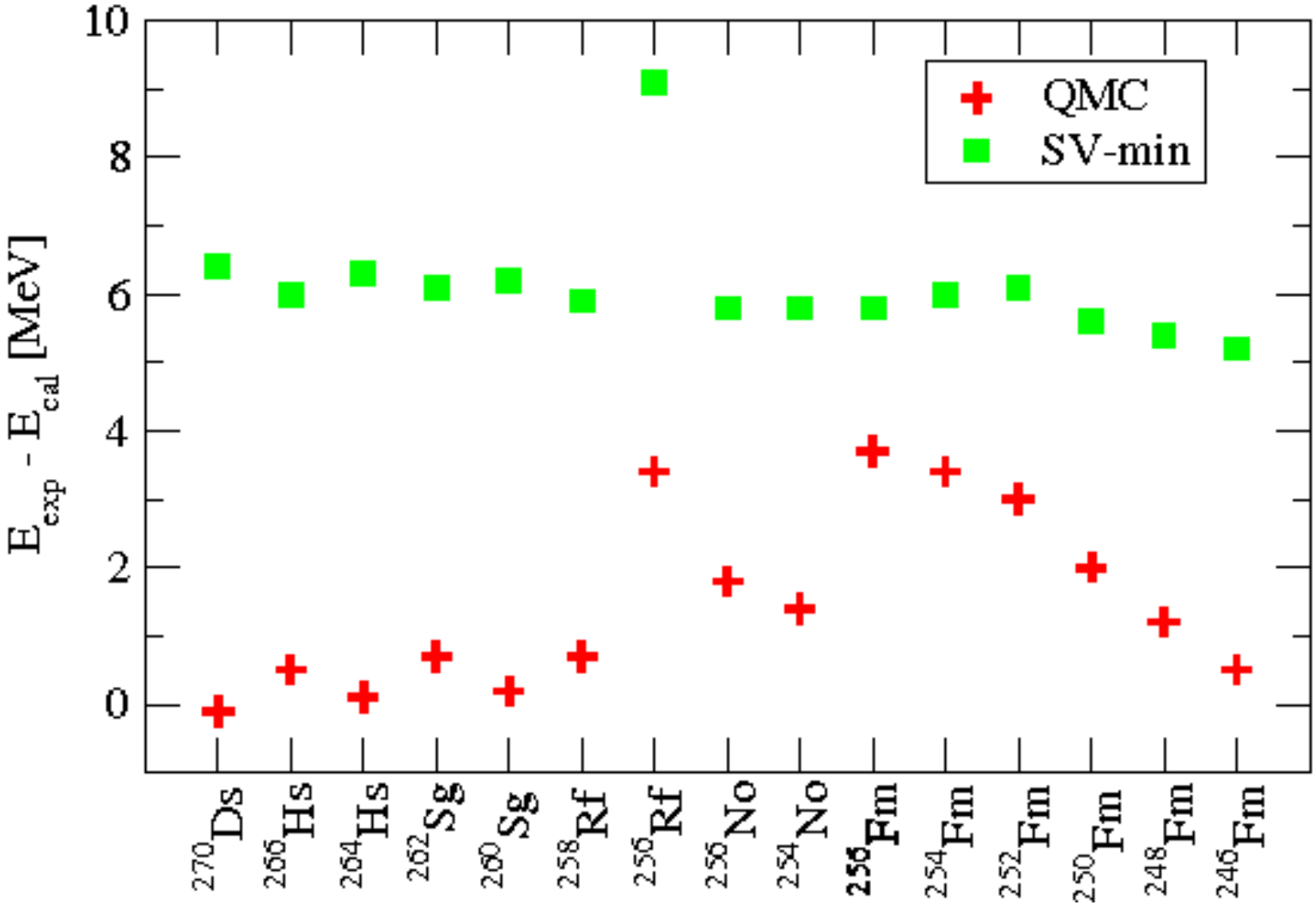
Overview

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

Superheavy Binding : 0.1% accuracy



Stone et al., PRL 116 (2016) 092501

For detailed study of SHE see: arXiv:1901.06064

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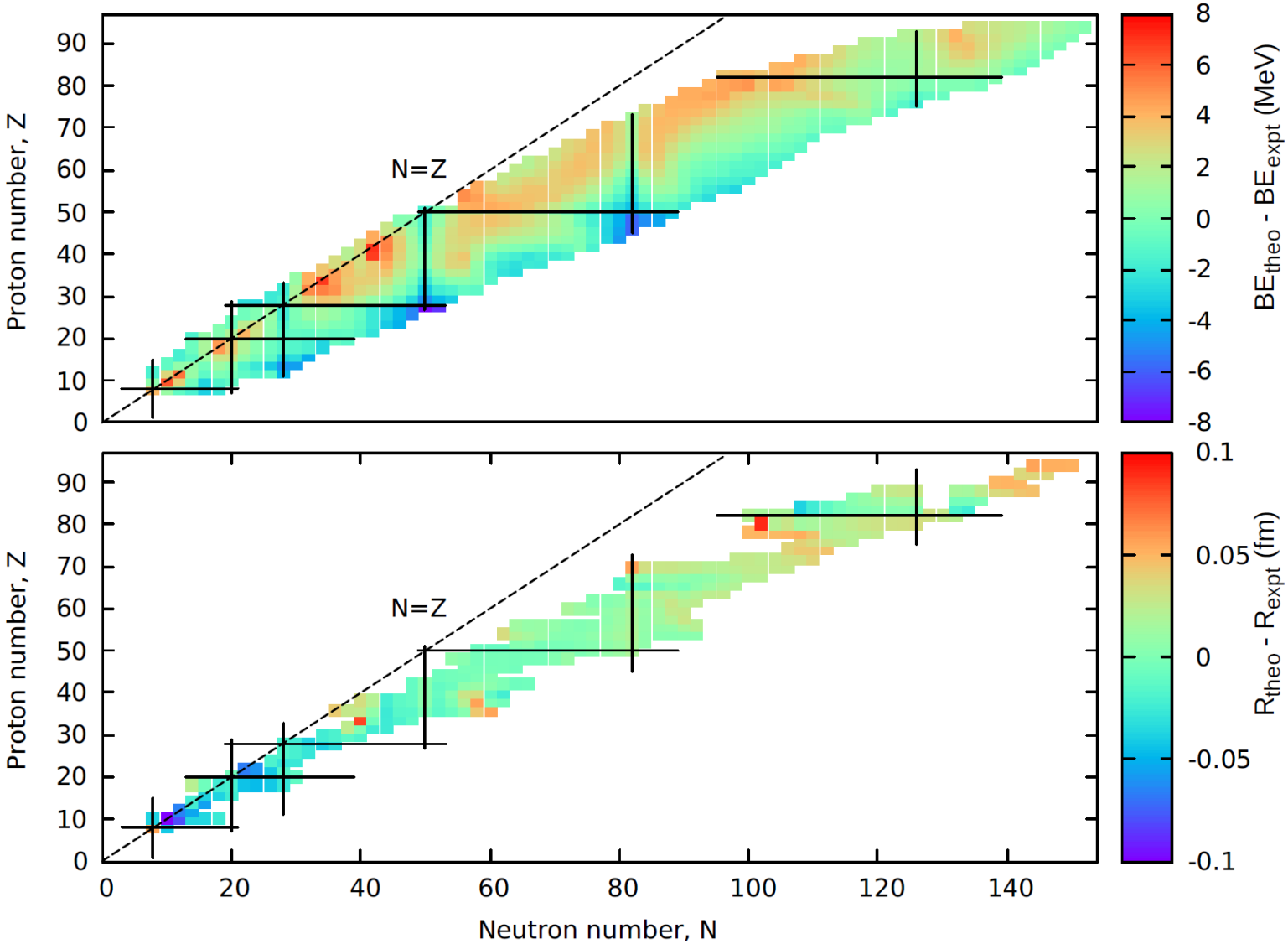
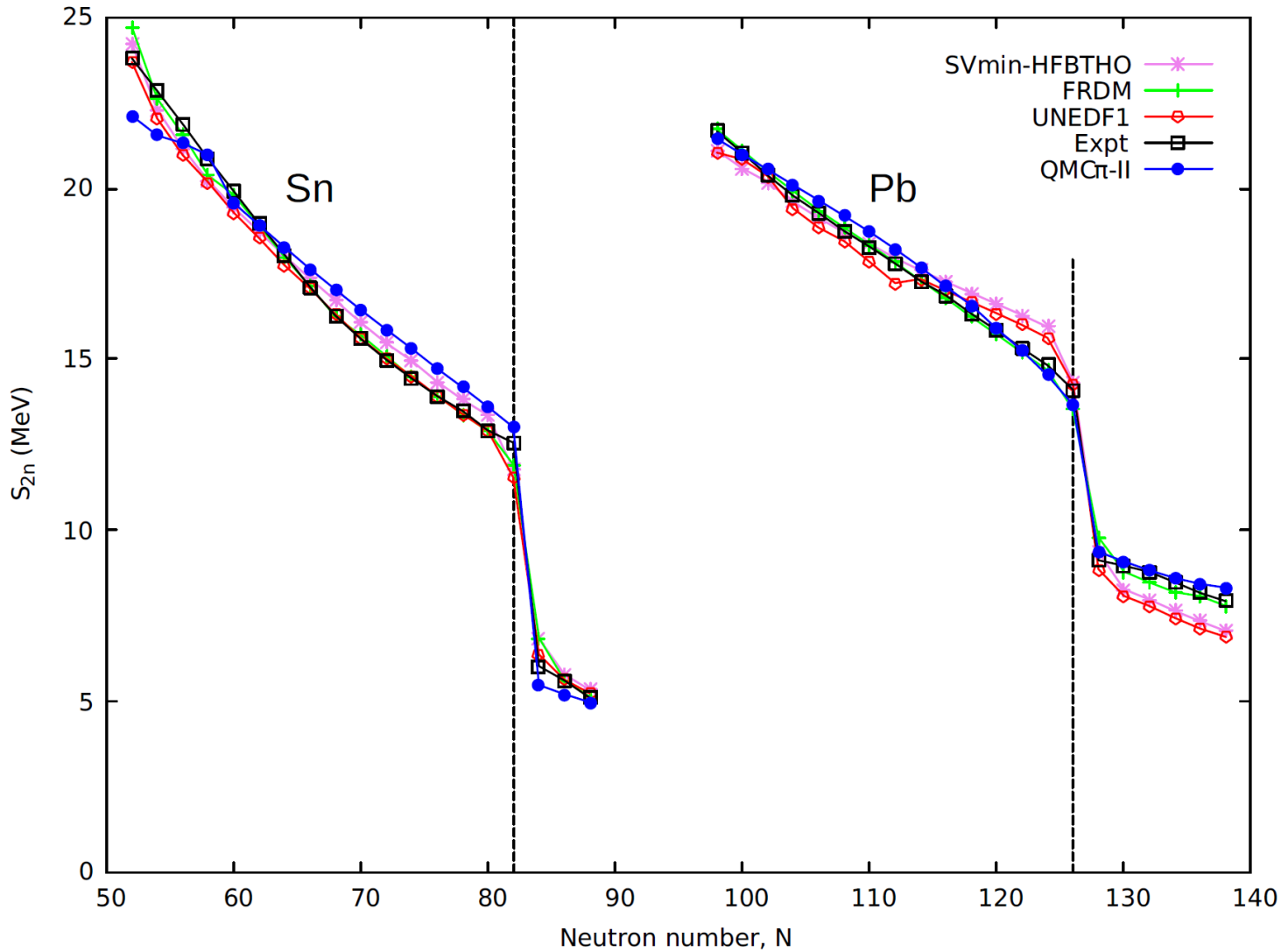
Overview of 739 even-even nuclei



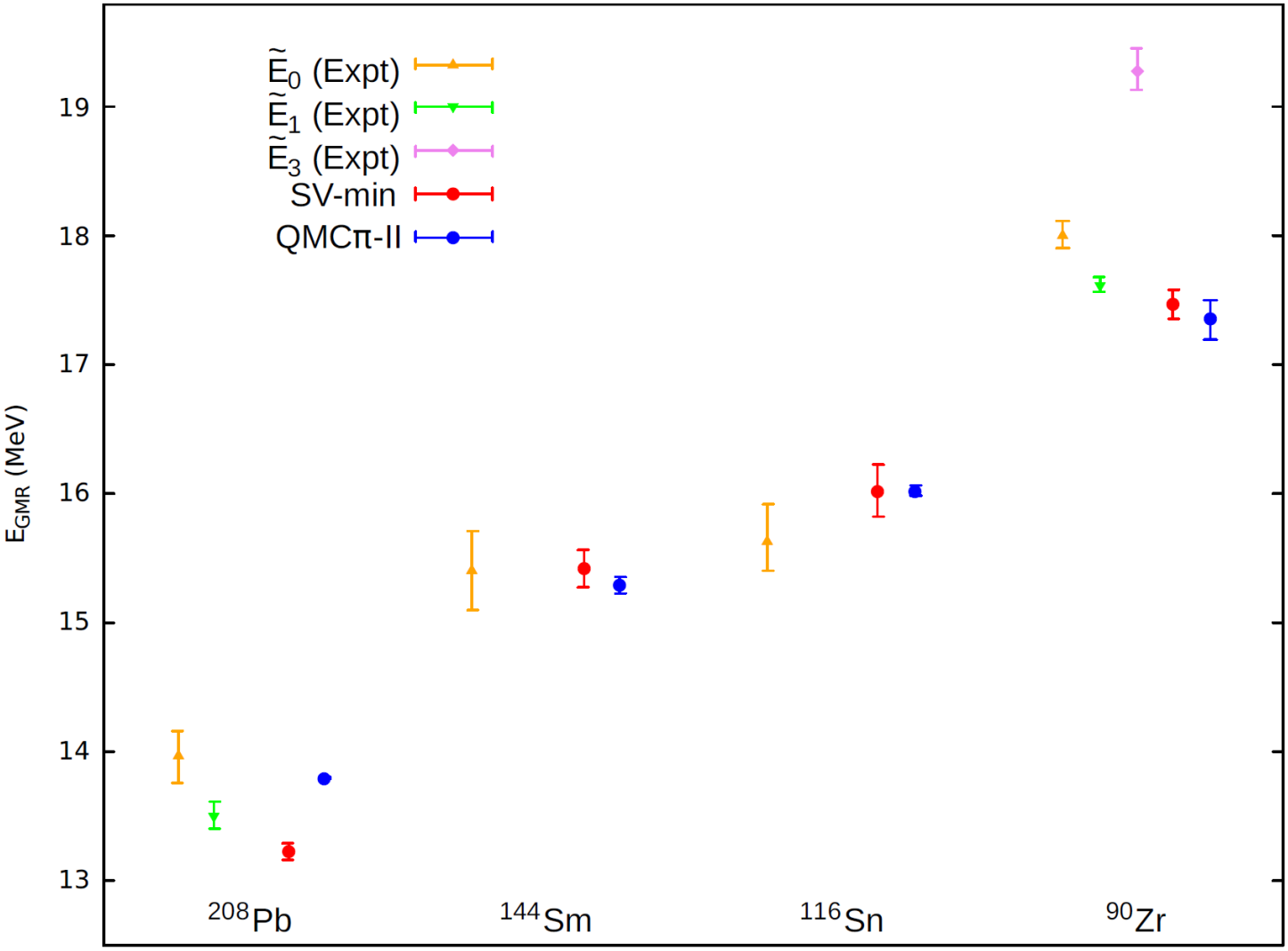
Martinez et al., arXiv:1811.06628

Systematics of two-neutron separation energy



Martinez et al., arXiv:1811.06628

Giant Monopole Resonance



Martinez et al., arXiv:1811.06628

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 (EMC effect)**
  - **elastic form factors.....**

EMC Effect

EMC Effect for Finite Nuclei

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

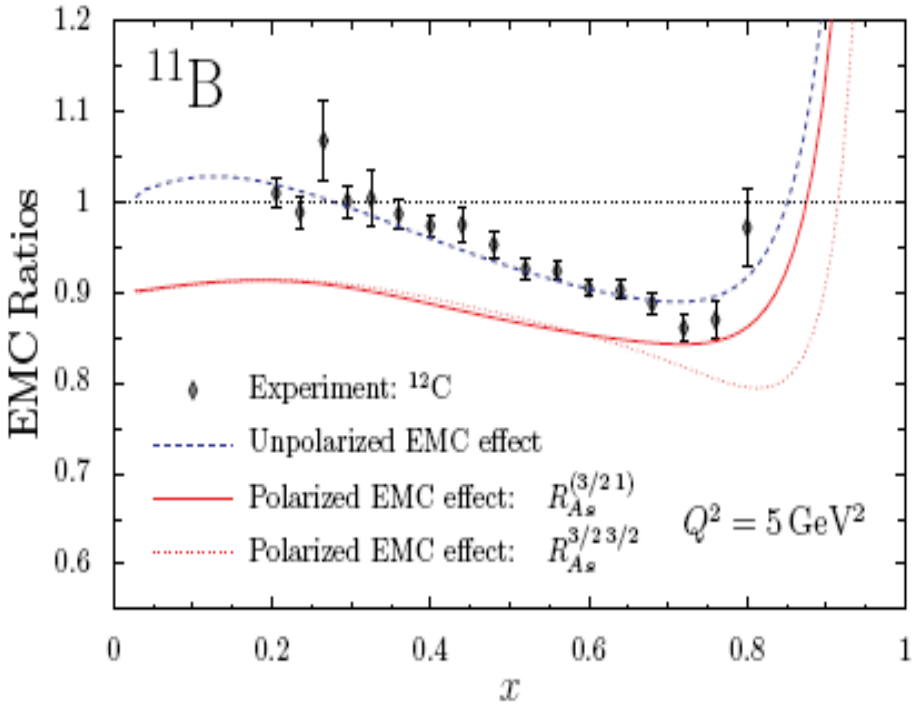


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

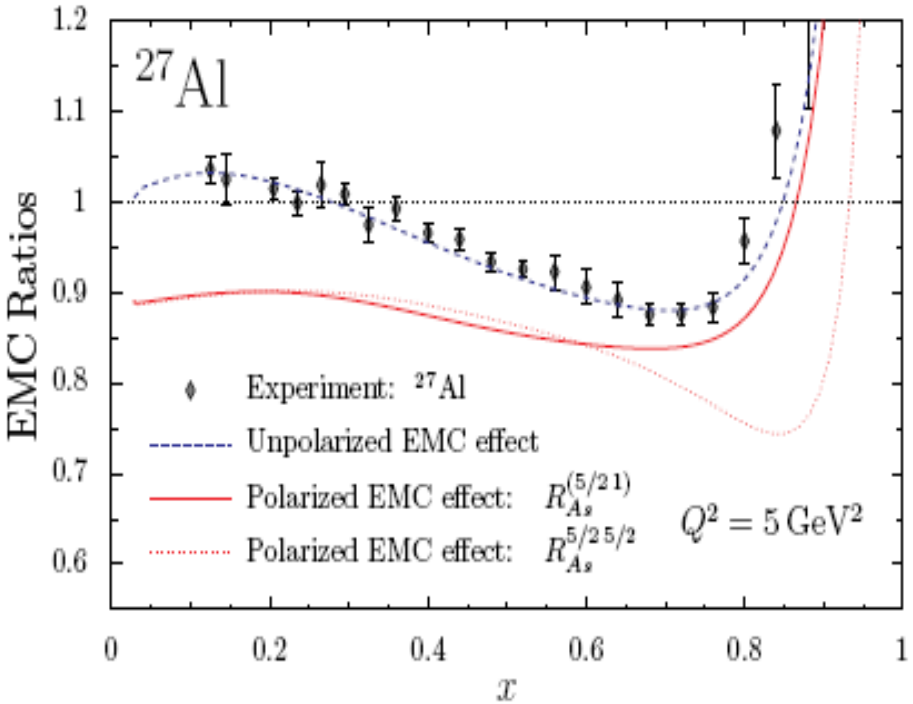
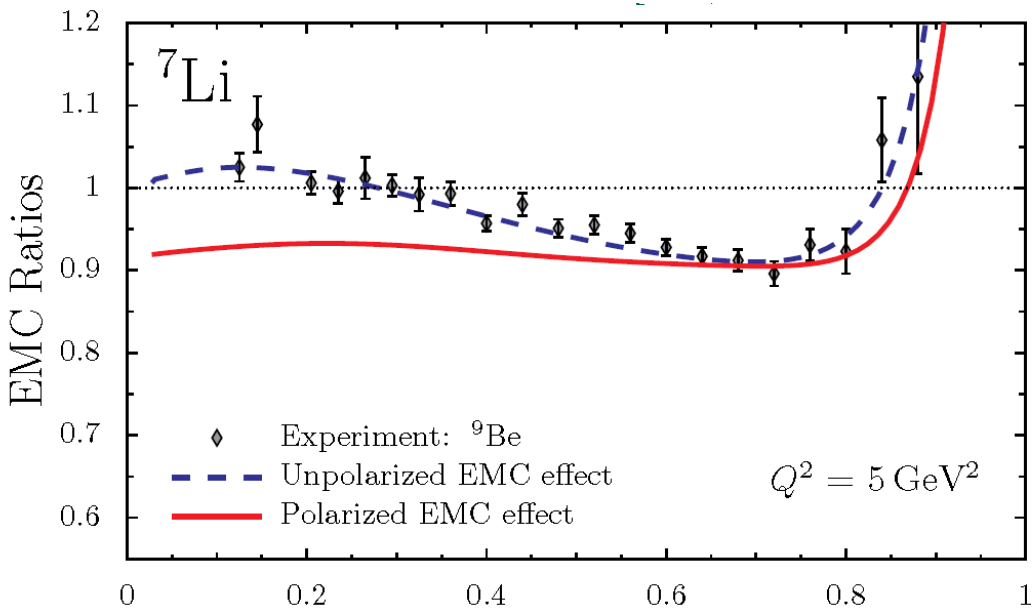


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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



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)

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 predicts essentially NO spin-EMC effect

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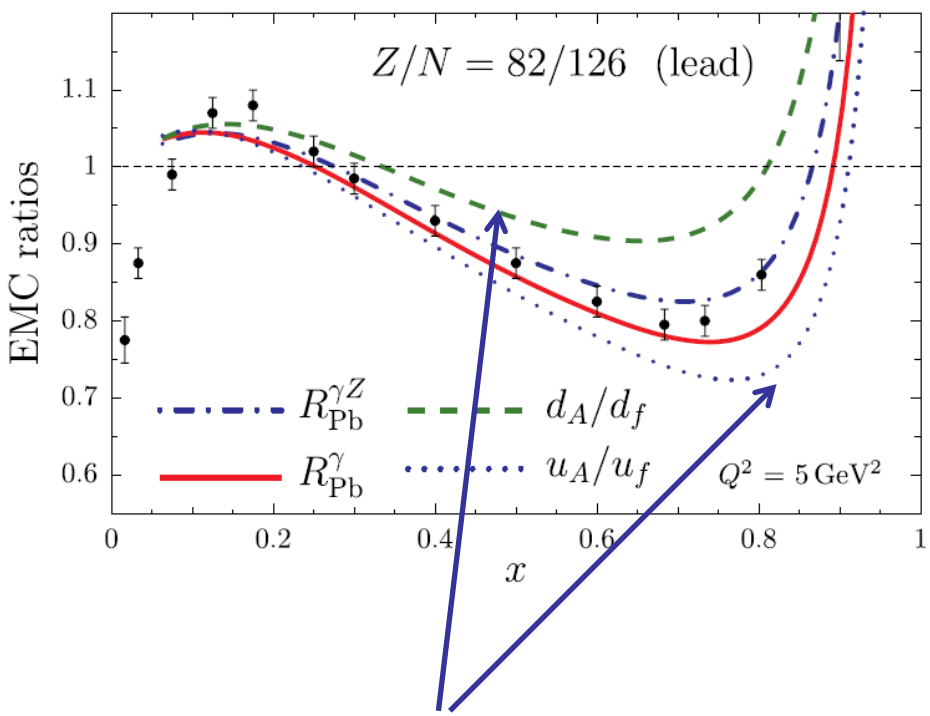
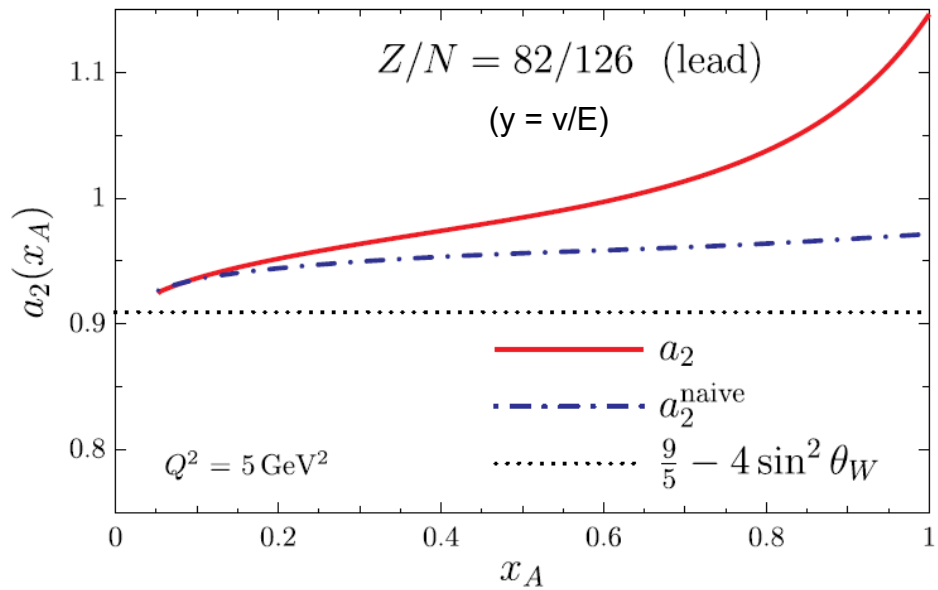
PRL 109, 182301 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

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]



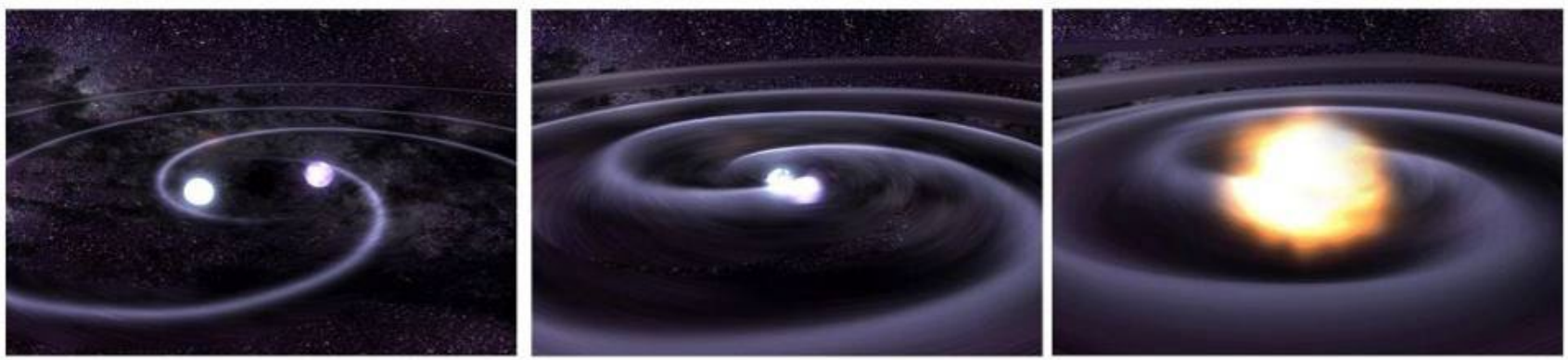
$$A_{\rm PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{\rm em}}\left[a_2(x_A) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x_A)\right]$$

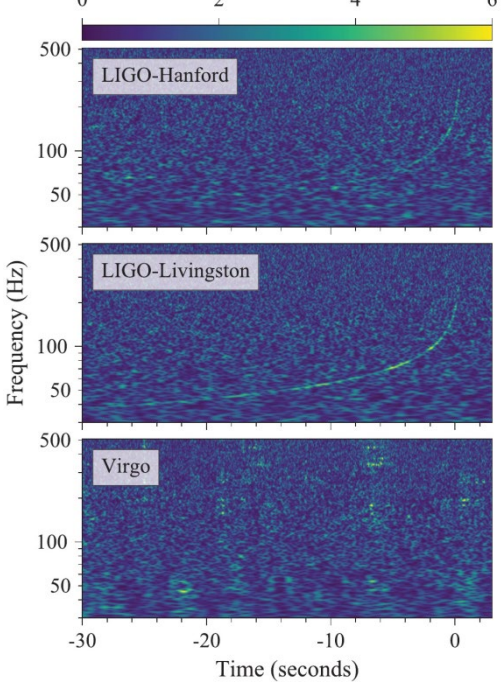


Ideally tested at EIC with CC reactions

Parity violating EMC will test this at JLab 12 GeV

Gravity Waves from Neutron Star Mergers





GW170817: Measurements of neutron star radii and equation of state

The LIGO Scientific Collaboration and The Virgo Collaboration

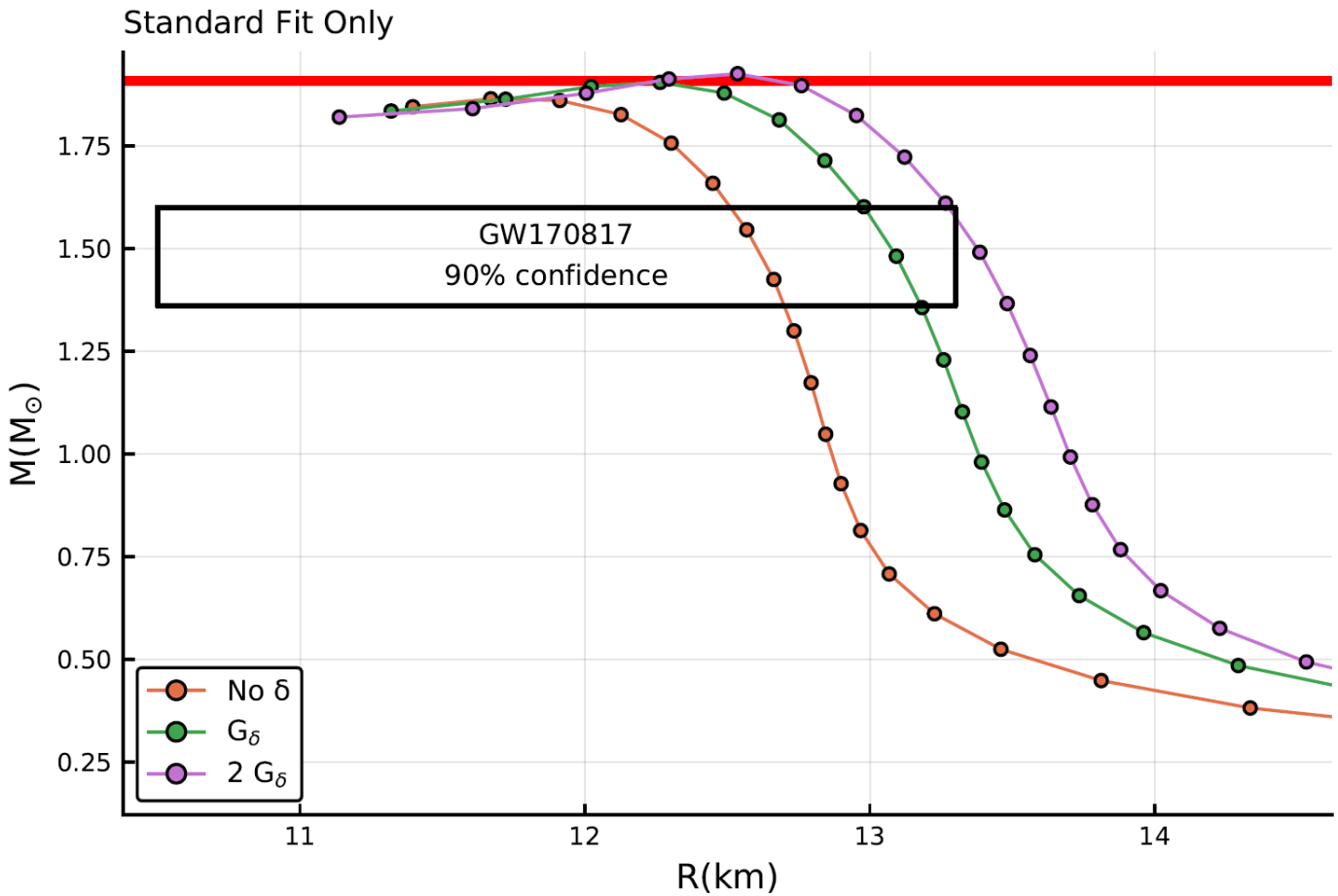
(compiled 30 May 2018)

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

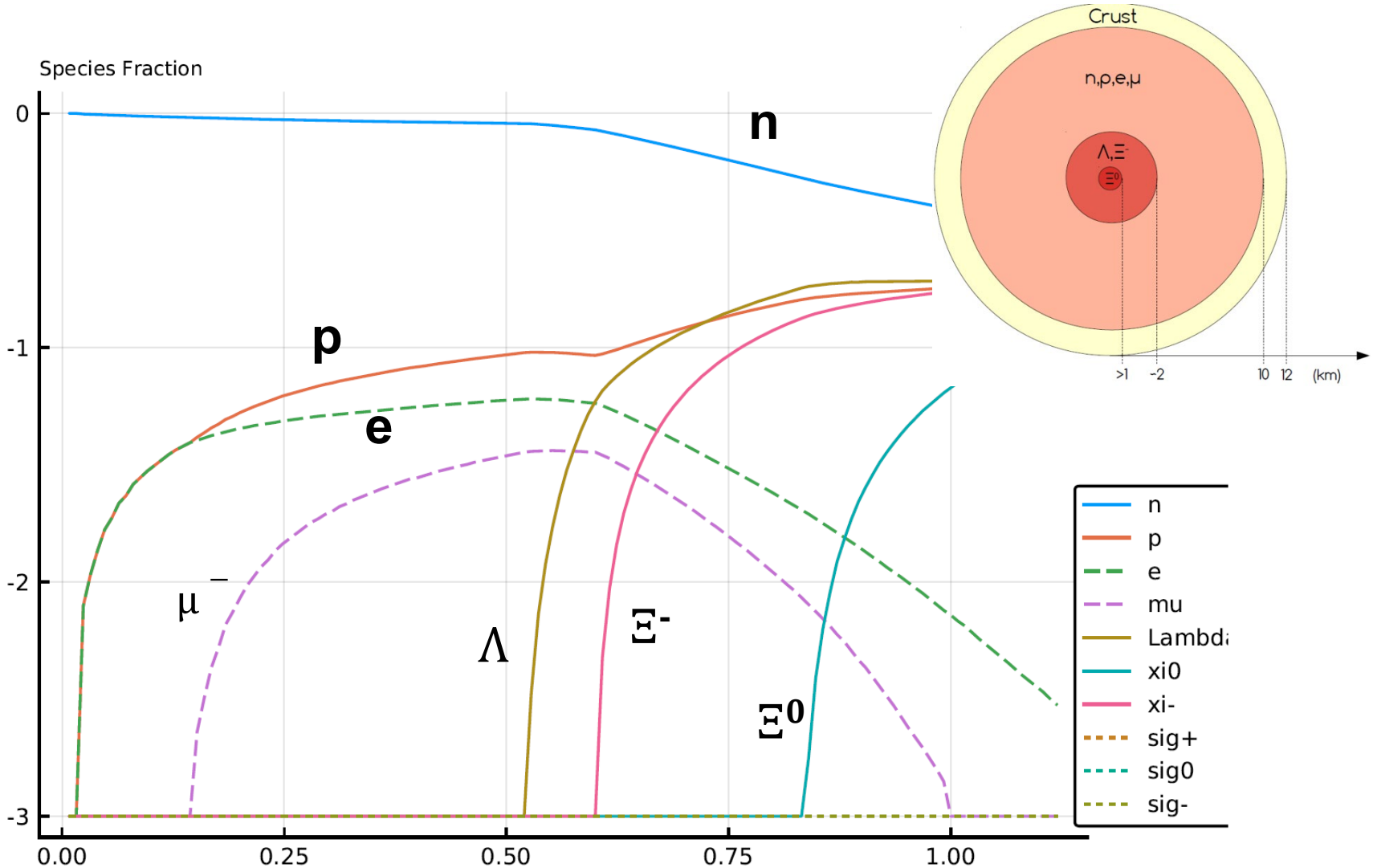
Recent Study Motivated by GW170817

- **Includes isovector scalar meson**



Motta, Kalaitzis *et al.*, ApJ 878:159 (2019)

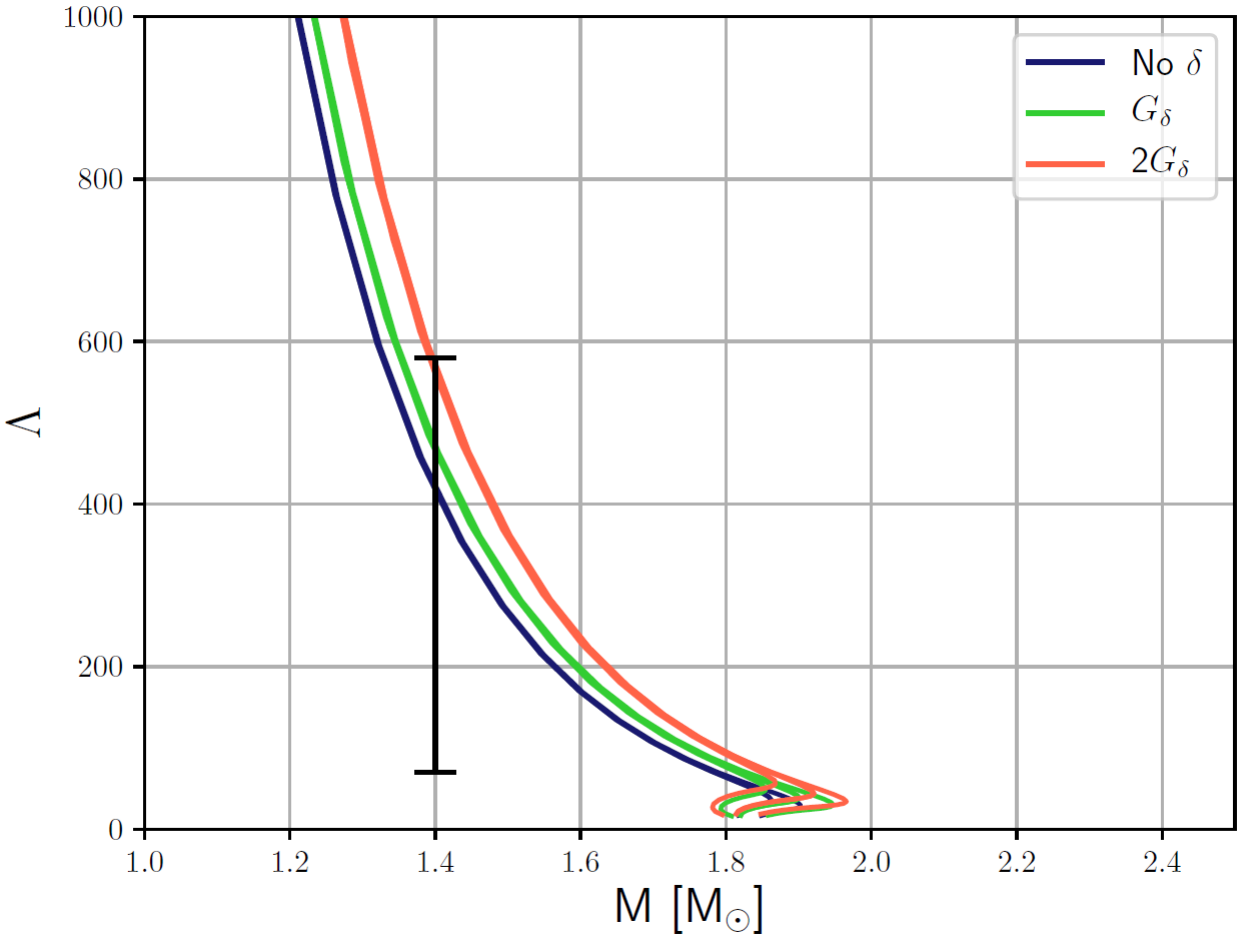
Species Fractions: in β-equilibrium

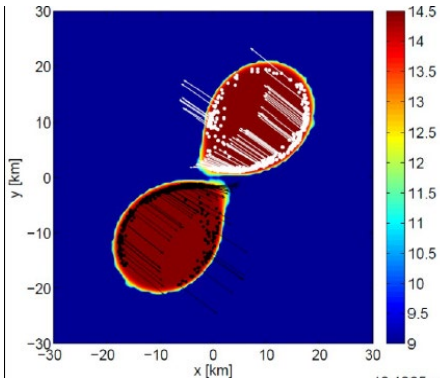


Motta, Kalaitzis *et al.*, ApJ 878:159 (2019)

Tidal deformability

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

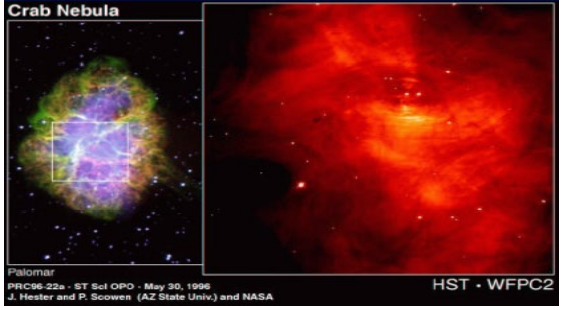




$$Q_{ij} = -\lambda(M)\, E_{ij}$$

Motta, Kalaitzis *et al.*, ApJ 878:159 (2019)

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

- **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 $2M_o$ *with hyperons***
  - Consistent with the tidal deformability deduced from GW170817

Special Mentions……

Guichon

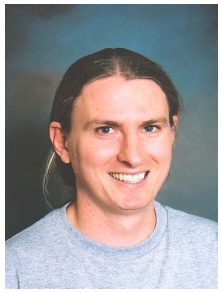
Tsushima

Saito

Stone

Krein

Matevosyan



Cloët

Whittenbury

Simenel

Bentz

Martinez

Motta

Kalaitzis

Latest papers

- **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

- **Neutron Stars**
  Motta et al., ApJ 878:159 (2019)
  Stone et al., arXiv:1906.11100

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)

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

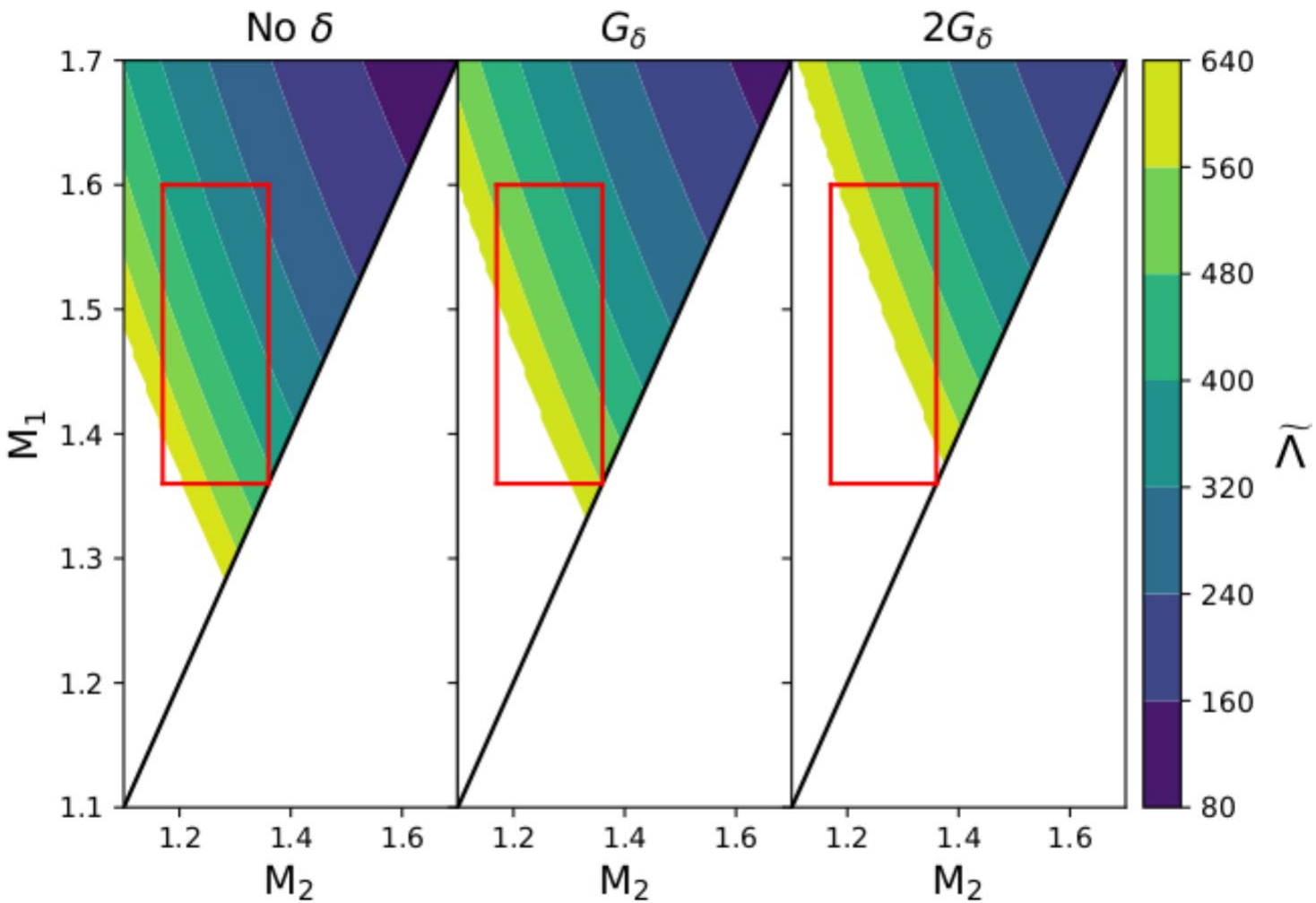
- Applications to neutron stars – including SQM:

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

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

Binary Tidal Deformability

- **Bound from De, Finstad, Lattimer et al. (2018)**



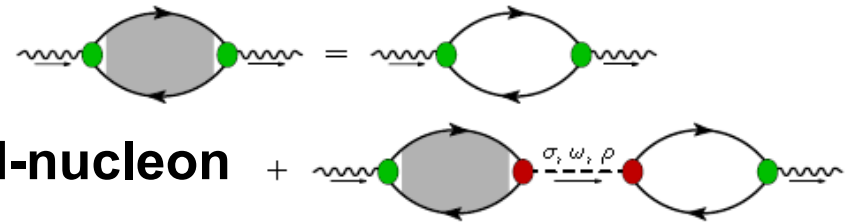
Motta, Kalaitzis *et al.*, ApJ 878:159 (2019)

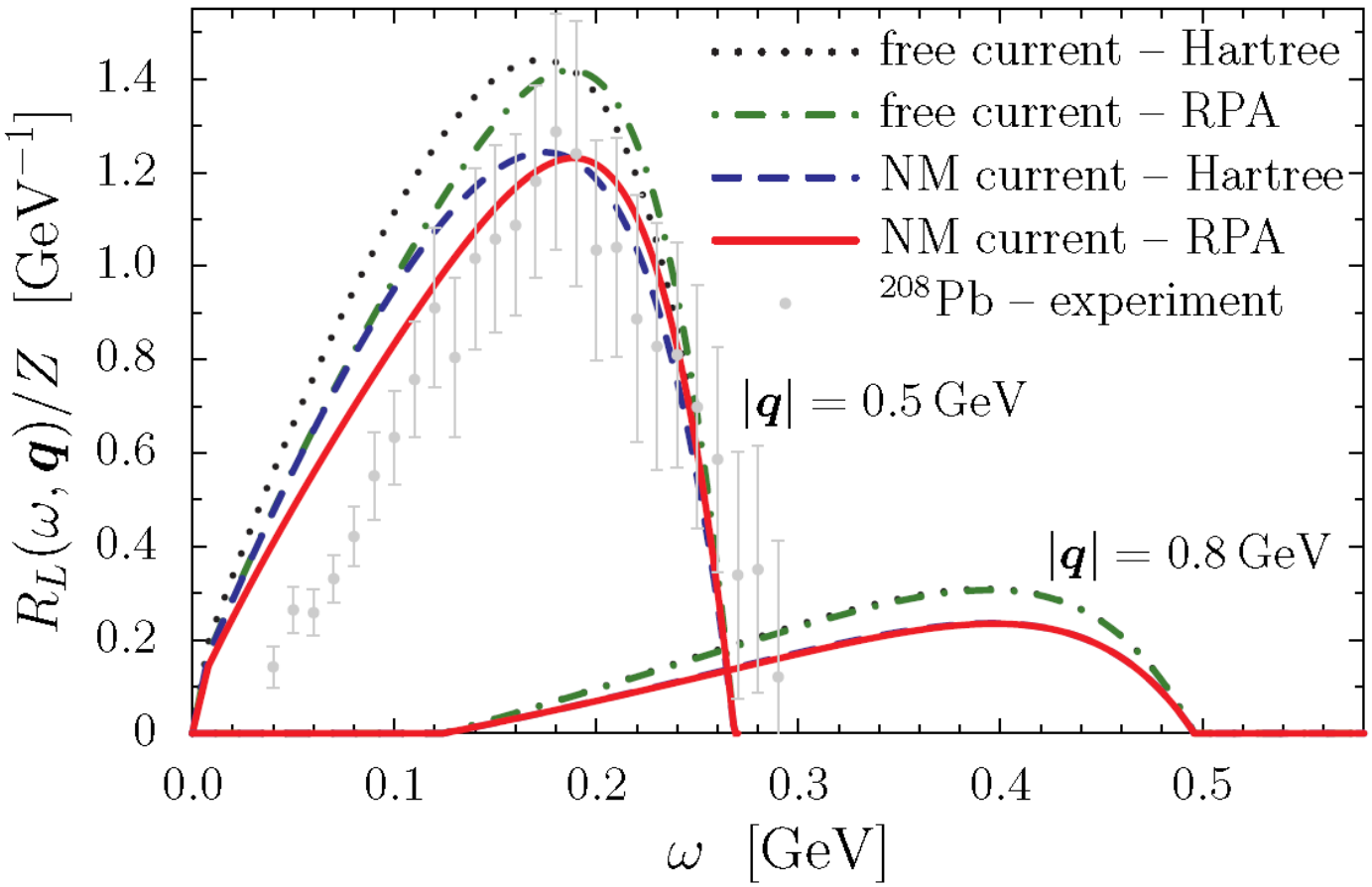
Modified Electromagnetic Form Factors In-Medium

Response Function

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

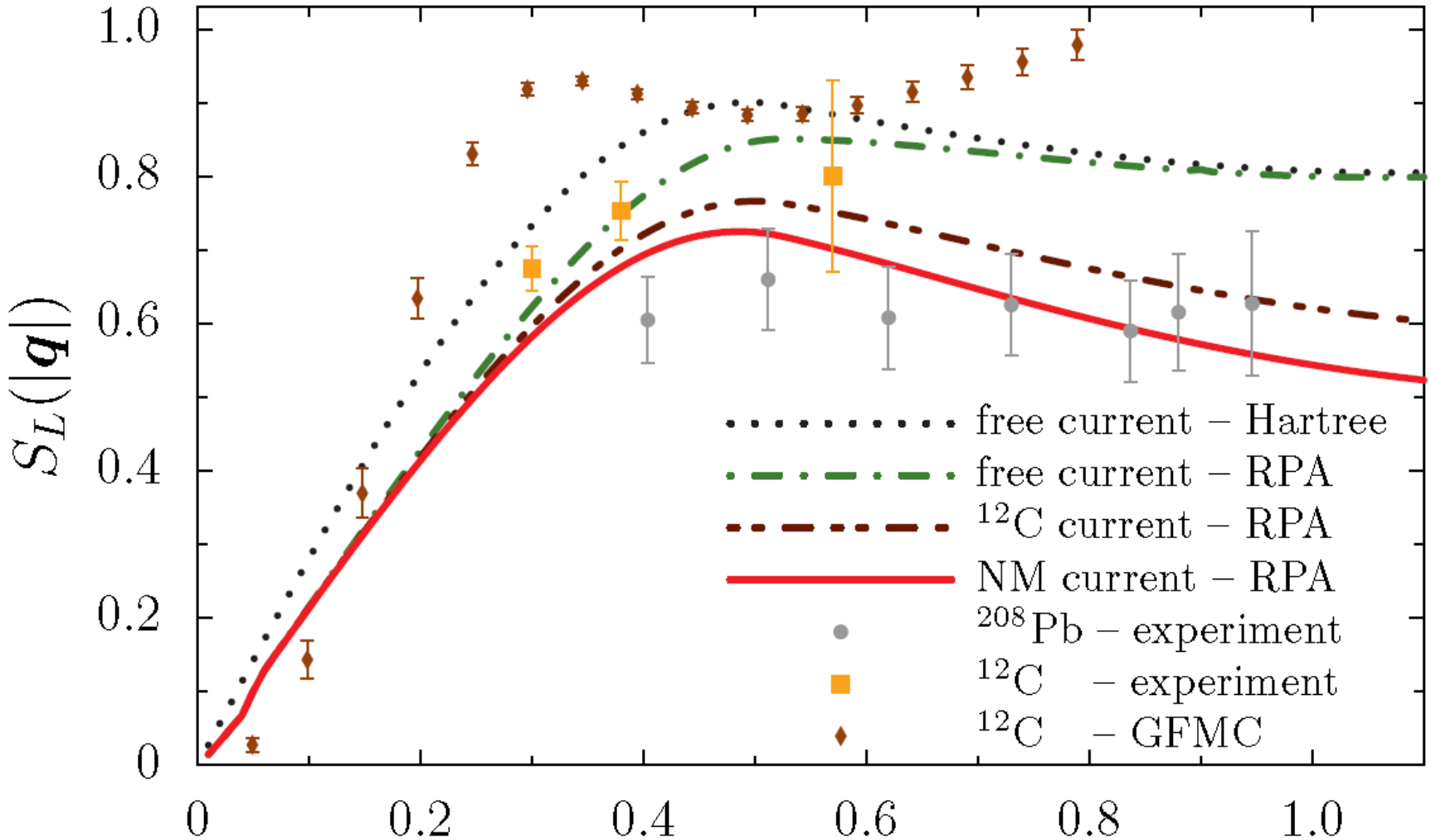
RPA correlations repulsive
Significant reduction in Response Function from the modification of bound-nucleon





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)