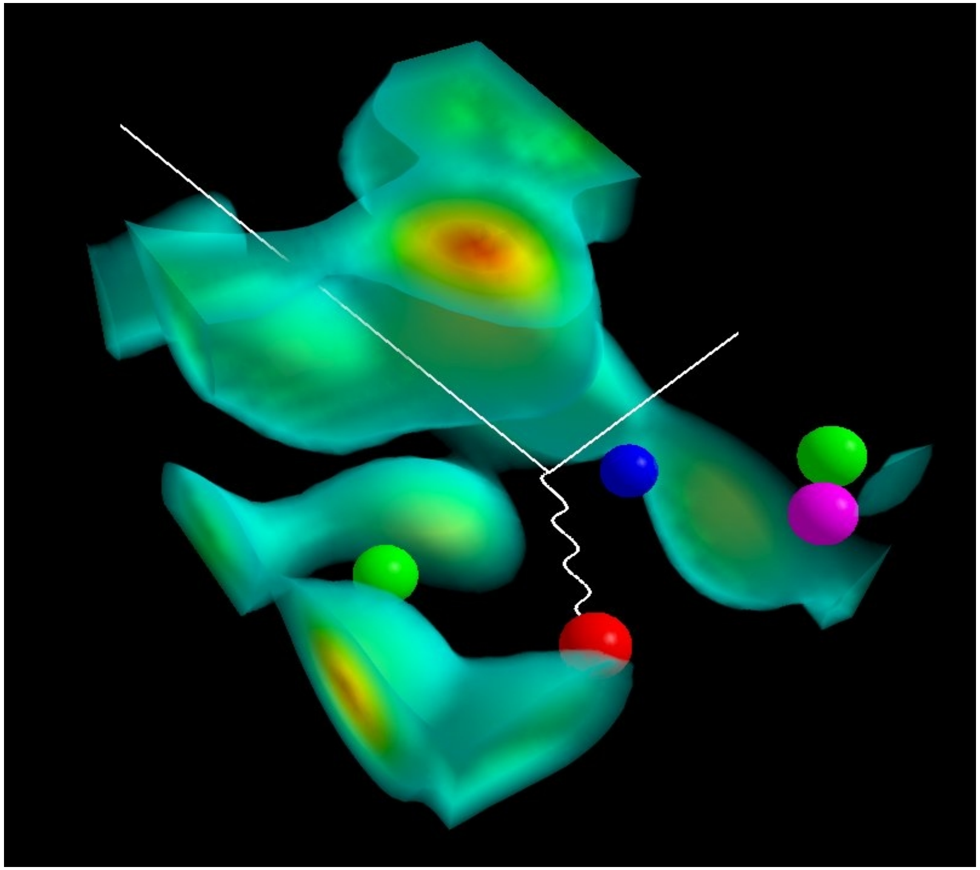
Nuclei to Neutron Stars: Starting at the Quark Level



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Anthony W. Thomas

Many Manifestations of Non-perturbative QCD
Cambury, Brazil : 30th April 2018

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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**

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I. Insights into nuclear structure

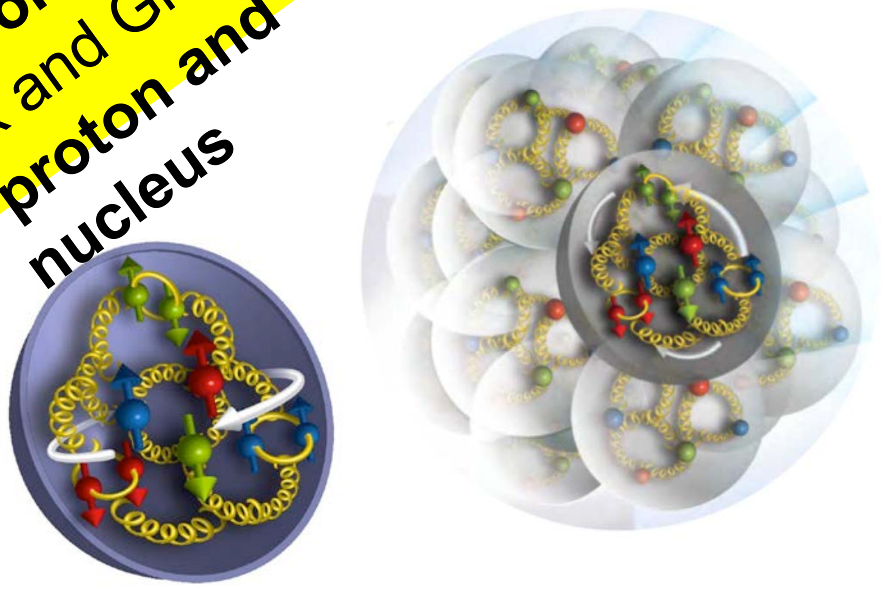
– what is the atomic nucleus?

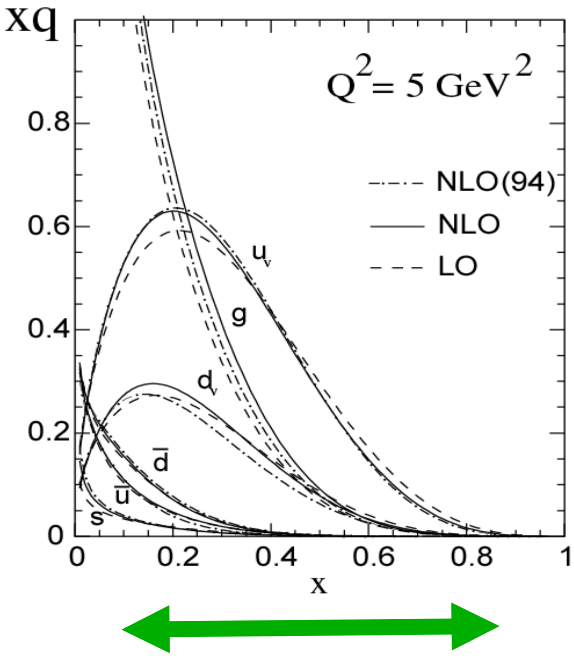
There are two very different extremes….

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 <u>not</u> 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 not interested in what is inside of a proton.”


©www.thomaspeschak.com

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

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

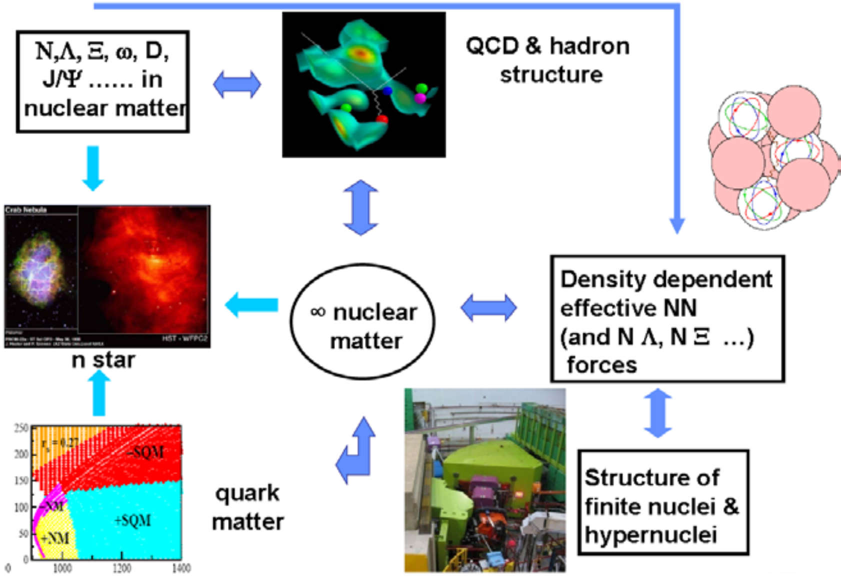
(Guichon, Saito, Tsushima et al., Rodionov et al.
- see Saito et al., Prog. Part. Nucl .Phys. 58 (2007) 1 and
Prog. Part. Nucl. Phys. 100 (2018) 262-297 for reviews)

- 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> (if σ mass fixed)

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



N,Λ, Ξ, ω, D, J/Ψ ...... in nuclear matter

QCD & hadron structure

∞ nuclear matter

Density dependent effective NN (and N Λ, N Ξ ...) forces

n star

quark matter

Structure of finite nuclei & hypernuclei

- Must solve <u>self-consistently</u> for the internal structure of baryons in-medium

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 EFFICIENT BECAUSE QUARKS ARE ALMOST MASSLESS)

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

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

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 functional:**

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

Derivation of effective Force (cont.)

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

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

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

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

Spin-orbit force predicted!

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 (+2 pairing pars)**

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

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Overview of 106 Nuclei Studied – Across Periodic Table

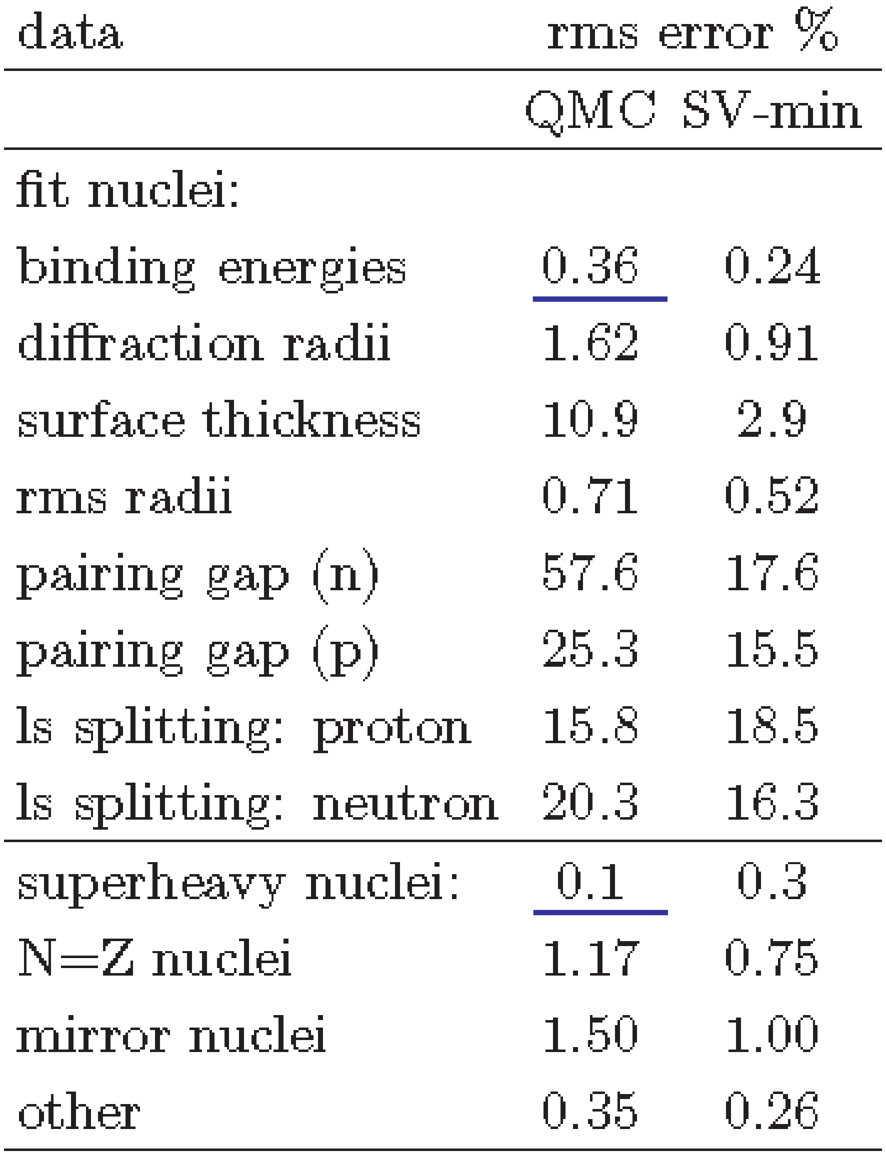
Element	Z	N	Element	Z	N
C	6	6 -16	Pb	82	116 - 132
O	8	4 -20	Pu	94	134 - 154
Ca	20	16 – 32	Fm	100	148 - 156
Ni	28	24 – 50	No	102	152 - 154
Sr	38	36 – 64	Rf	104	152 - 154
Zr	40	44 -64	Sg	106	154 - 156
Sn	50	50 – 86	Hs	108	156 - 158
Sm	62	74 – 98	Ds	110	160
Gd	64	74 -100			

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

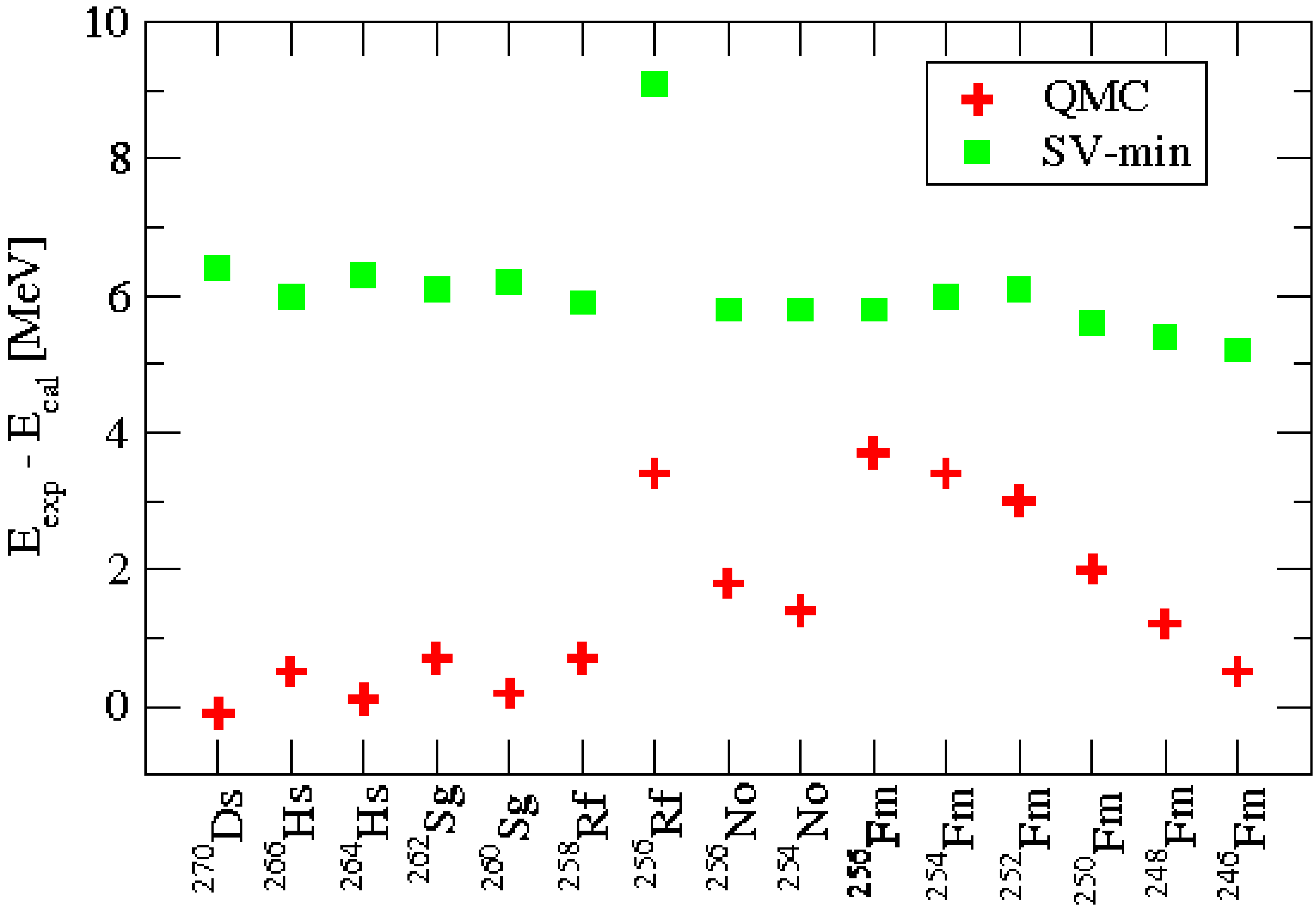
Overview



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

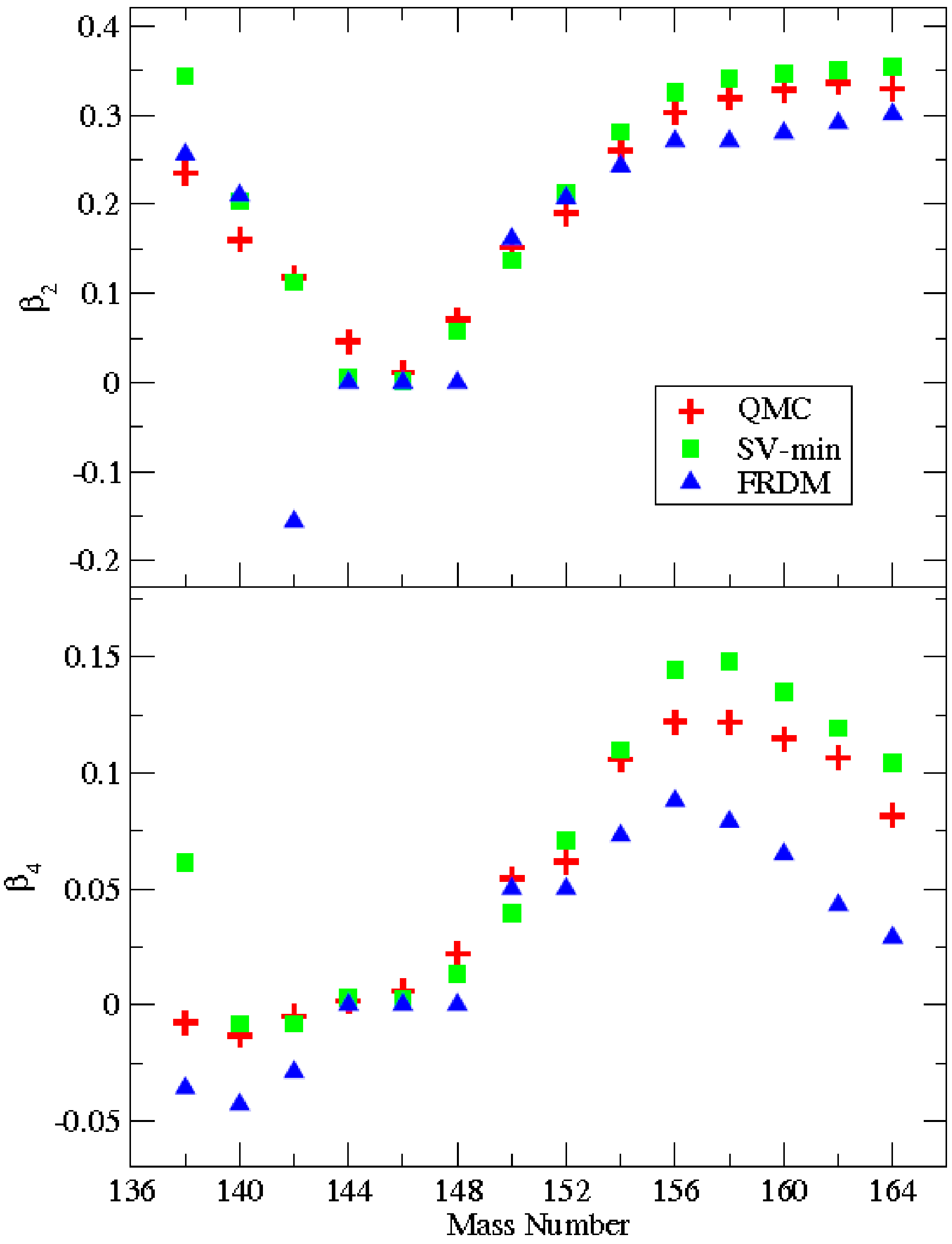
Stone et al., PRL (2016)

Superheavy Binding : 0.1% accuracy



Stone et al., PRL 116 (2016) 092501

Deformation in Gd (Z=64) Isotopes



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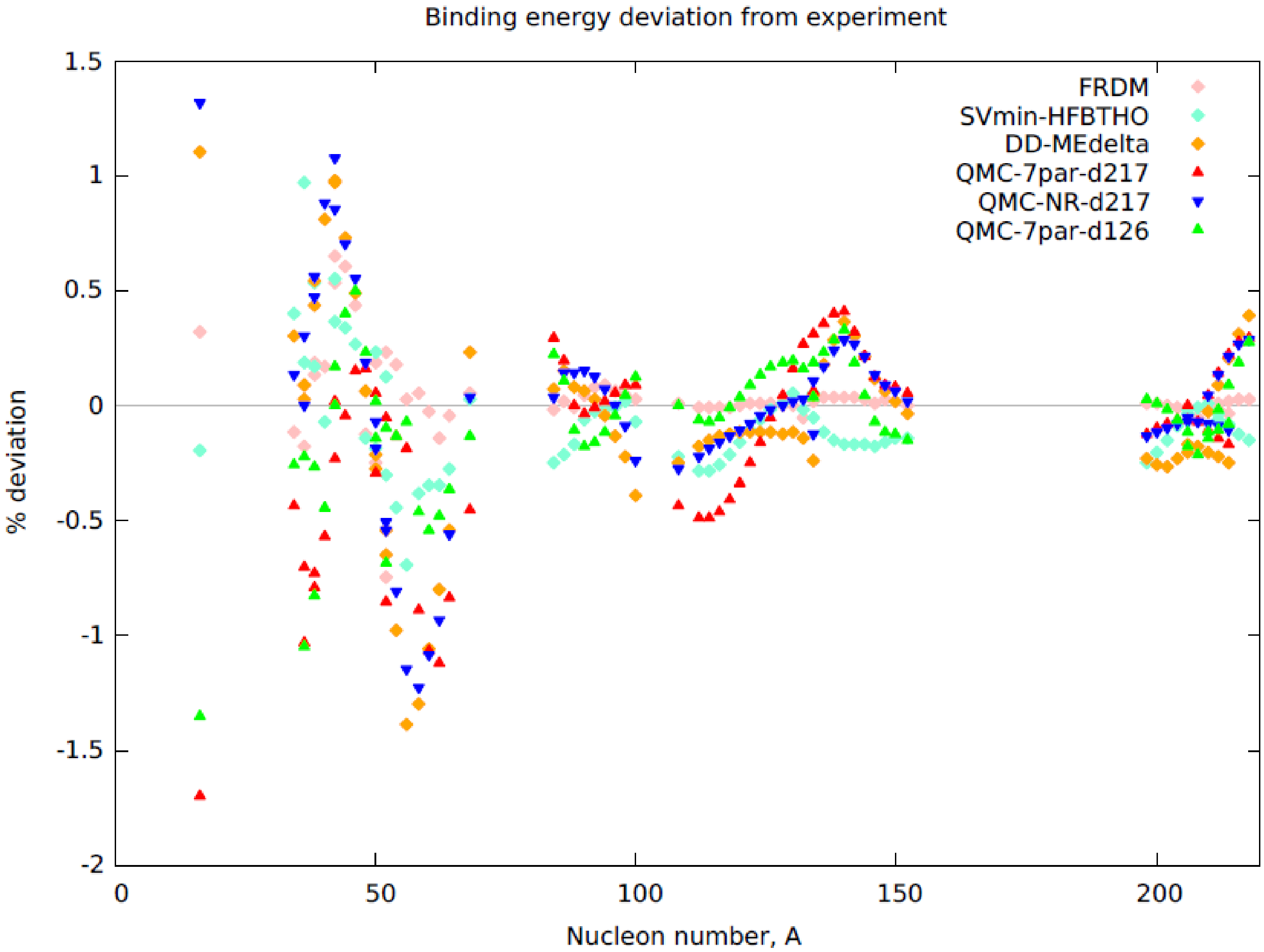
Extended QMC – Martinez, Konieczka, Bąszyk *et al.*
- *implement QMC EFD in HFODD*



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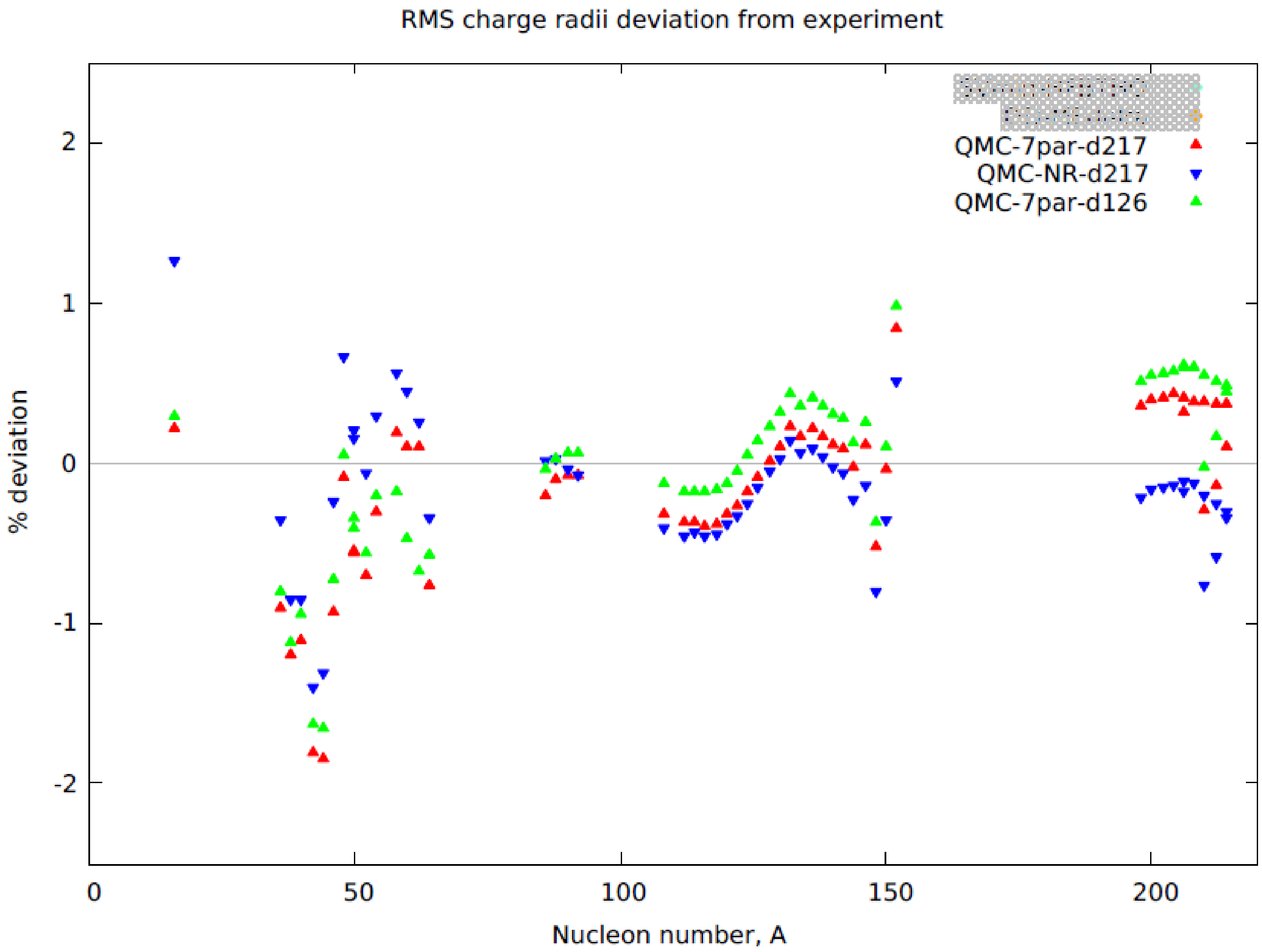
Extended QMC – Martinez, Konieczka, Bąszyk *et al.*



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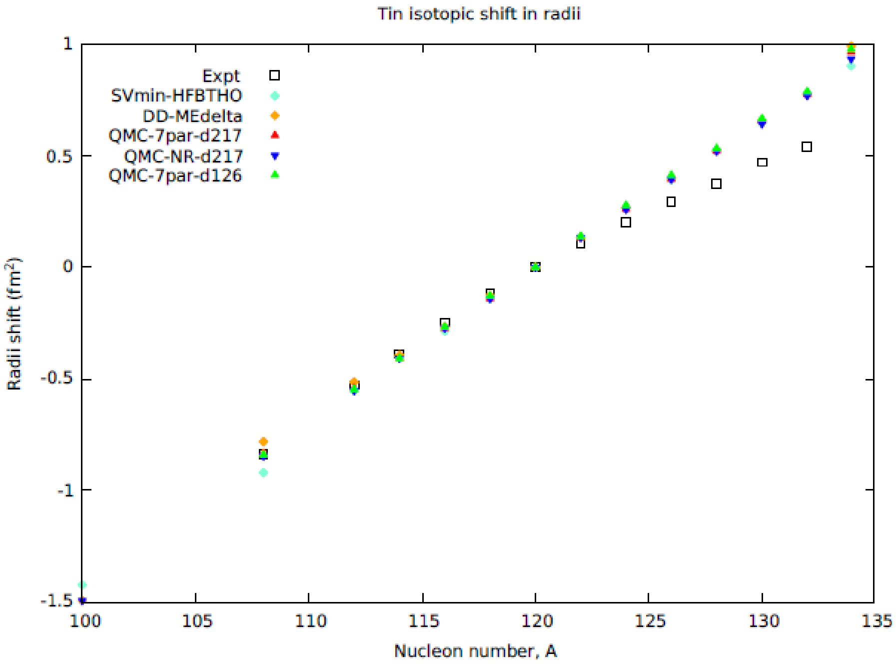
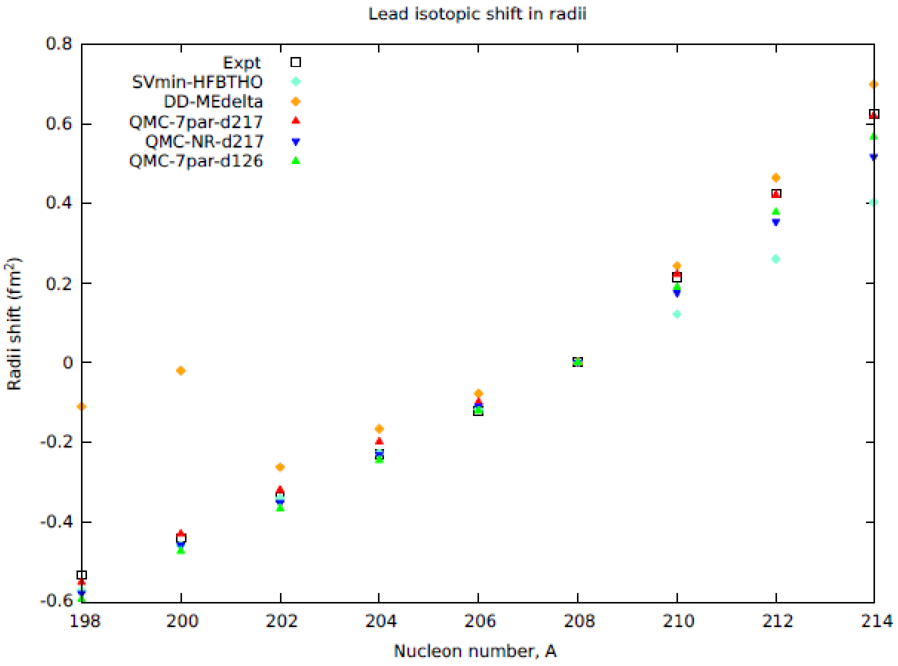
Extended QMC – Martinez, Konieczka, Bąszyk *et al.*

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





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**

EMC Effect for Finite Nuclei

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

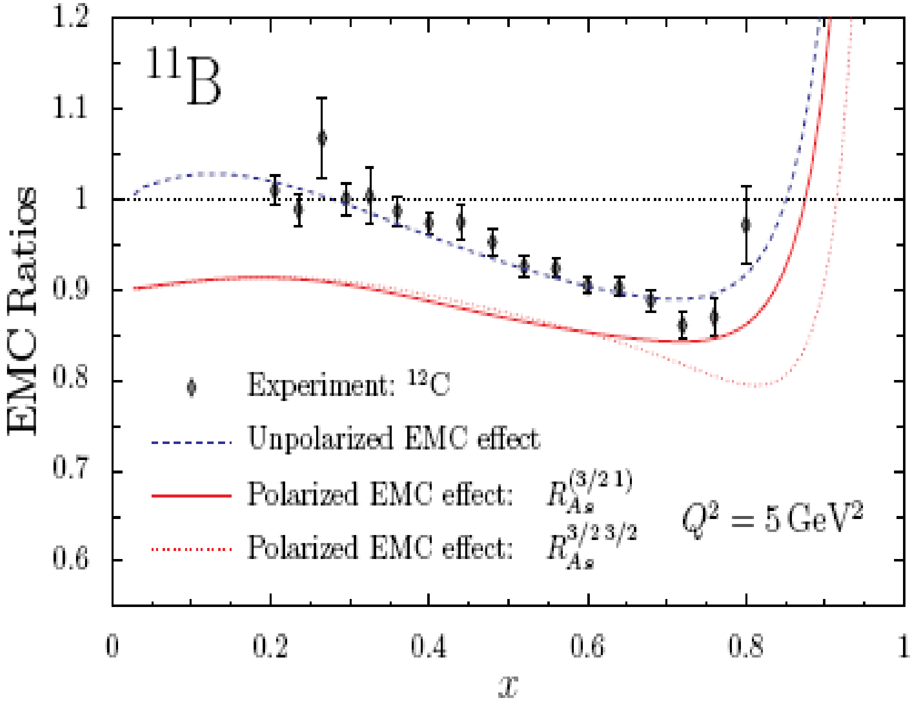


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

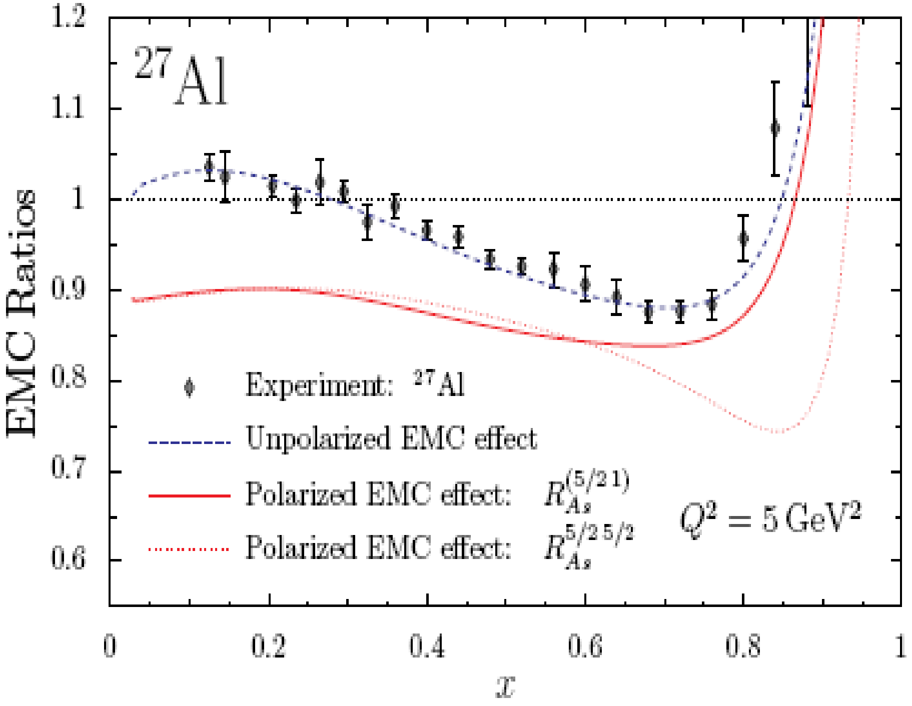
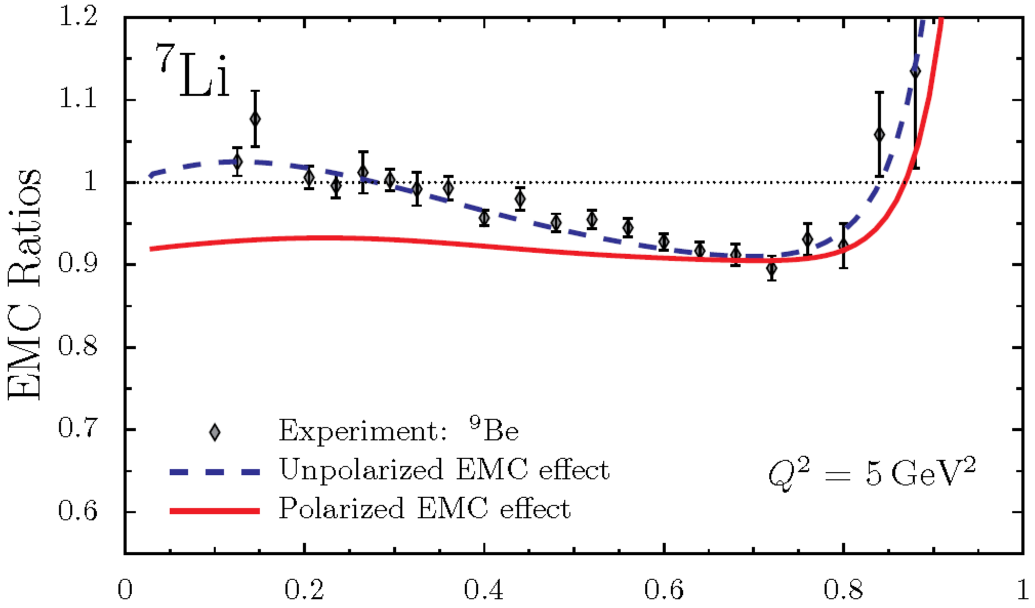


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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

Approved JLab Experiment

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



Other tests (e.g. Isovector EMC effect)

Isovector EMC Effect

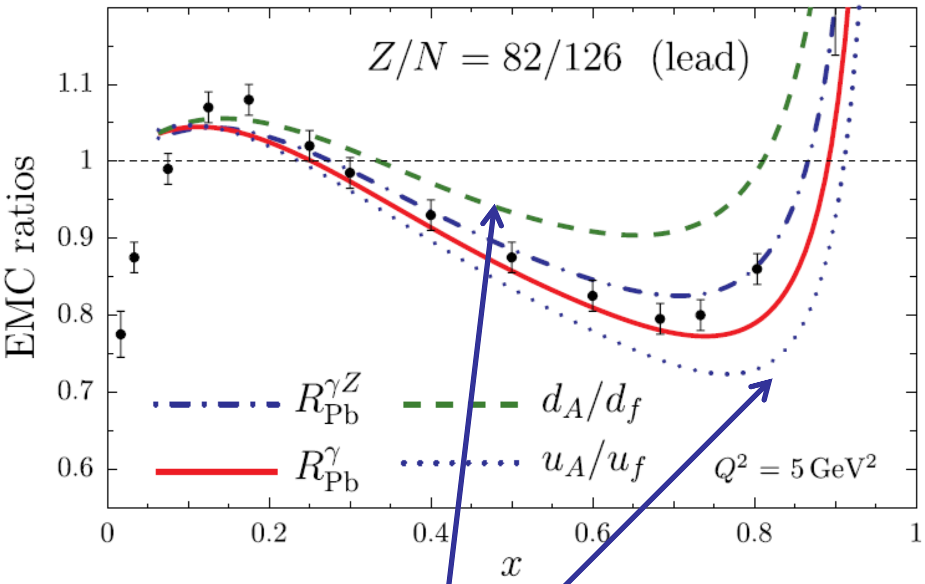
- New realization concerning EMC effect in this approach:
  - isovector force in nucleus (like Fe) with N≠Z effects ALL u and d quarks in the nucleus
  - subtracting structure functions of extra neutrons is not enough
  - *there is a shift of momentum from all u to all d quarks*
- Sign and magnitude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

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

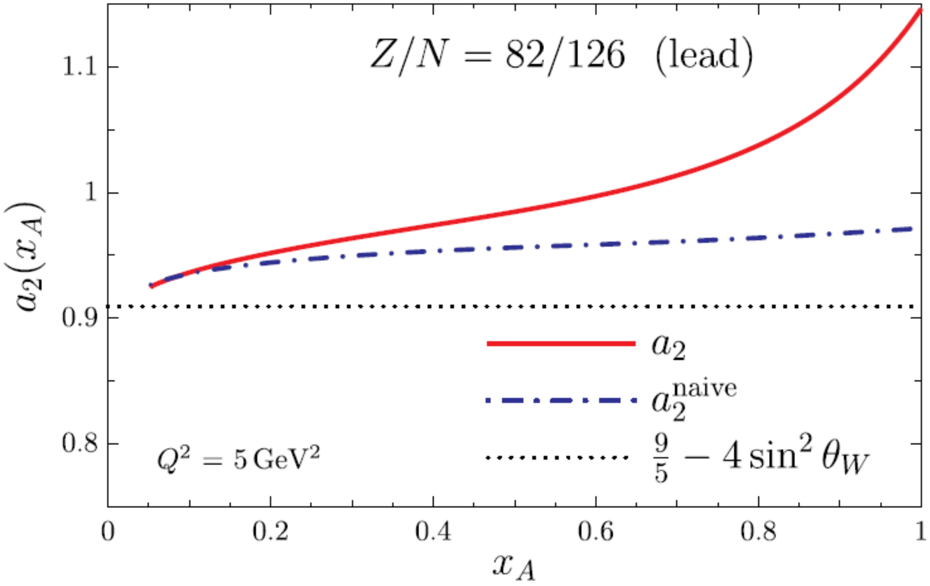
PRL 109, 182301 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

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]



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



Ideally tested at EIC with CC reactions

Parity violating EMC will test this at JLab 12 GeV

Comment on EMC explanation in terms of SRC

- **It is crucial to have experimental signatures which might distinguish the mean field modification from an effect arising solely from SRC**

- **Isovector EMC effect: difference between effect on *u* and *d* quarks is much smaller in SRC approach**

- **Spin EMC effect is essentially absent in SRC approach**

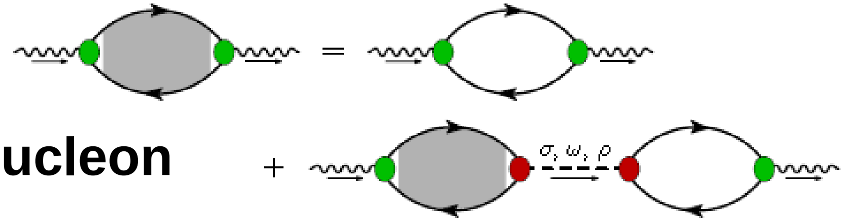
Modified Electromagnetic Form Factors In-Medium

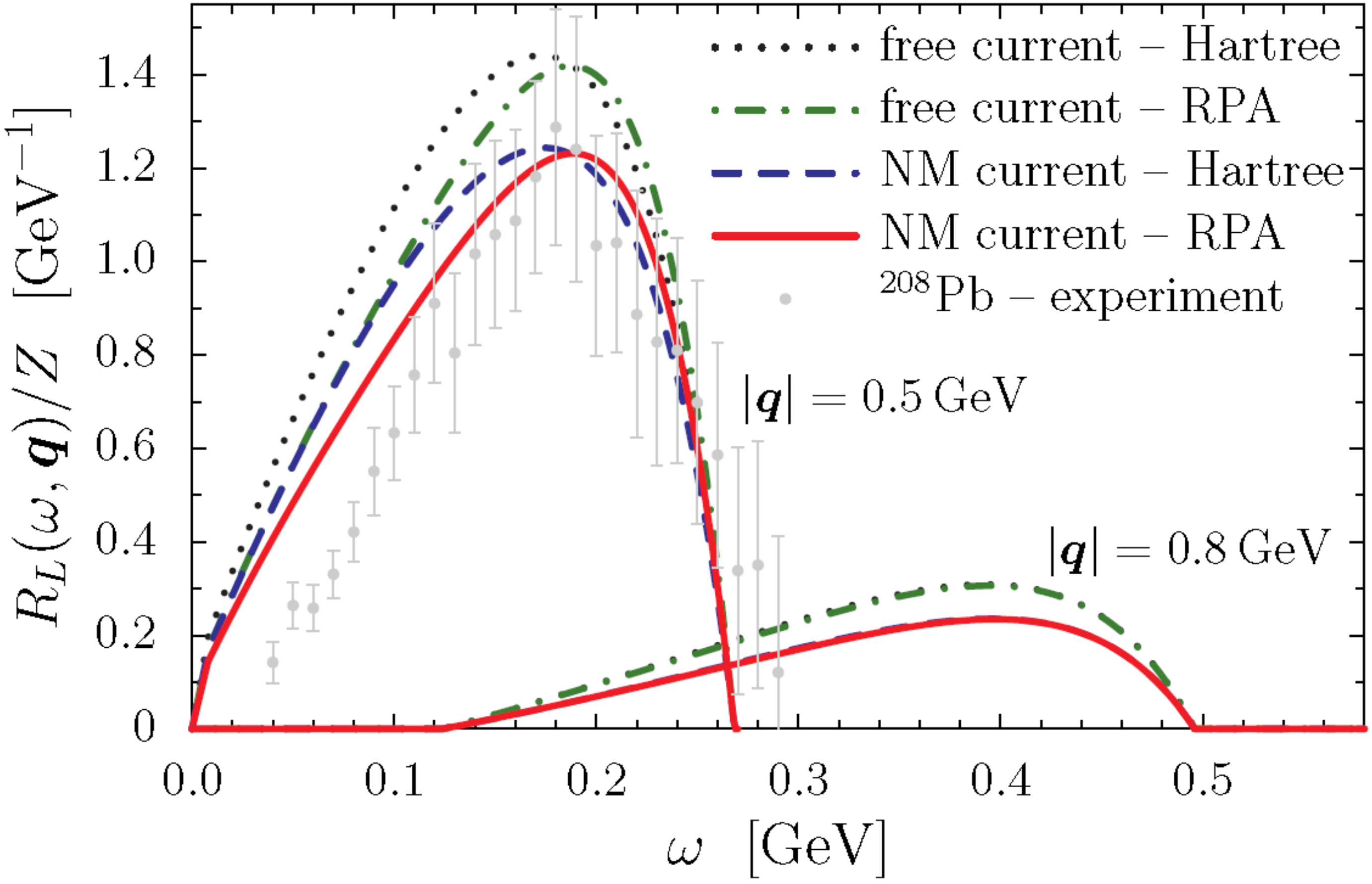
Response Function

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

RPA correlations repulsive

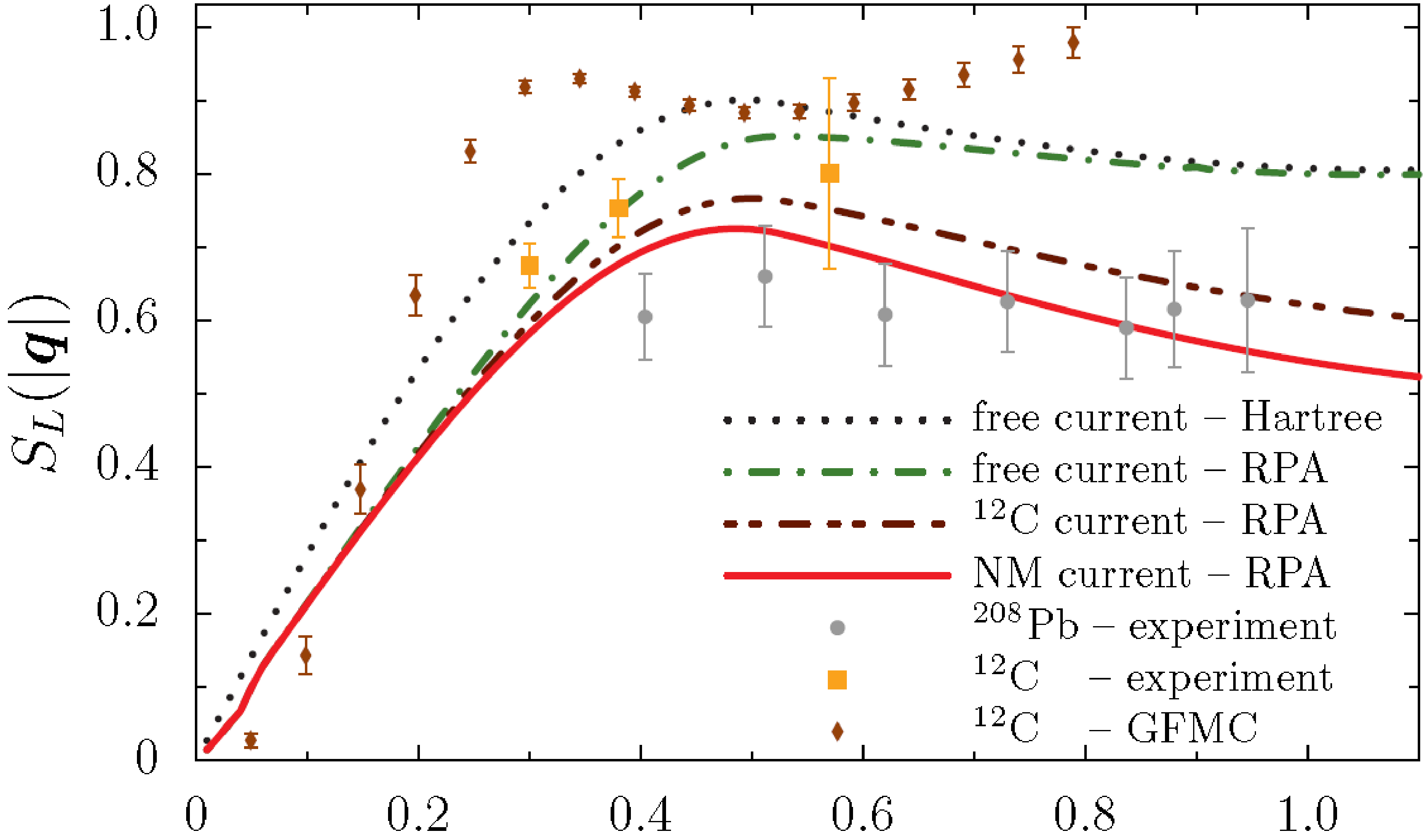
Significant reduction in Response Function from modification of bound-nucleon





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

Comparison with Unmodified Nucleon & Data

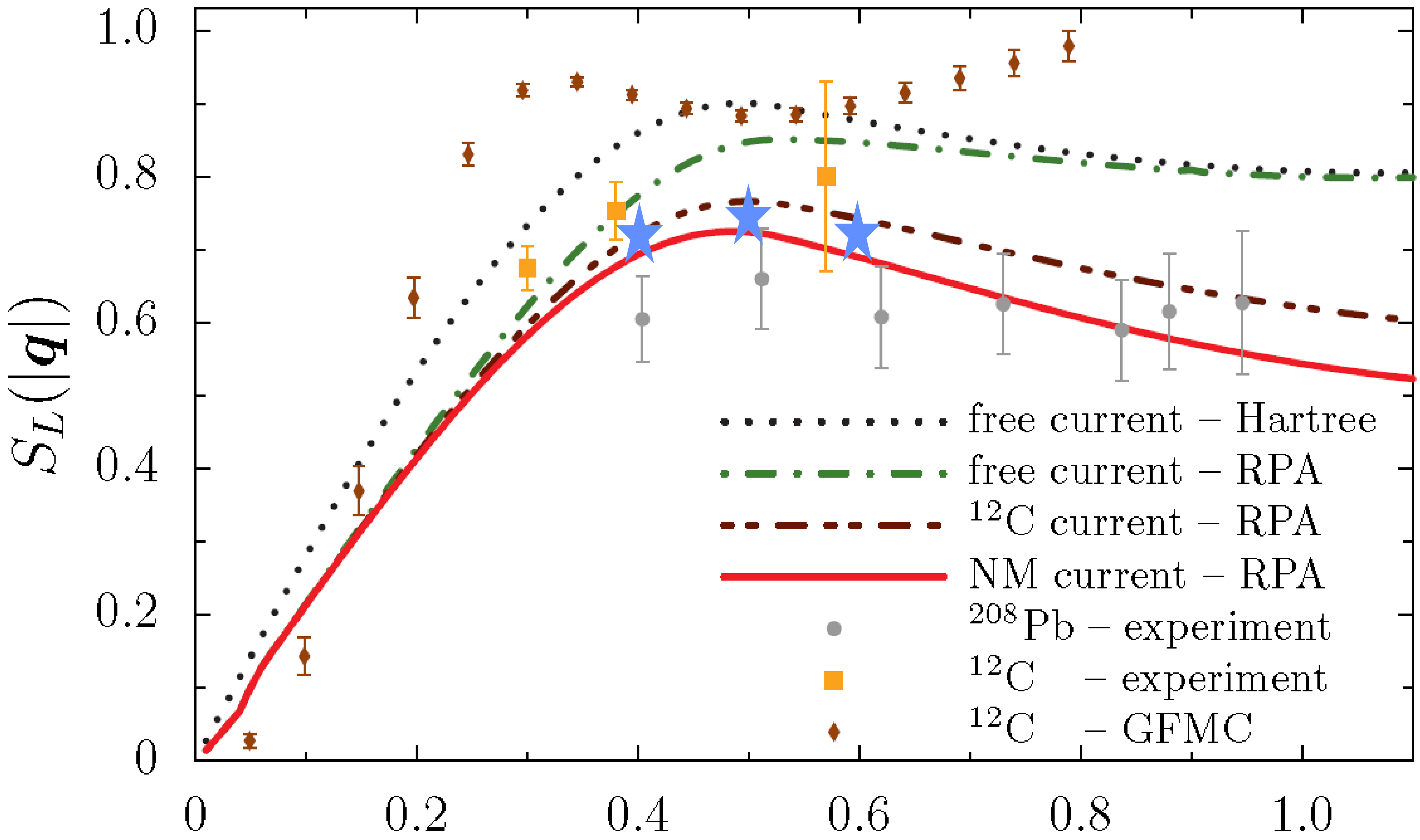


$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|q|} d\omega \, \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)}$$

Data: Morgenstern & Meziani

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

and these predictions are stable!



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

★ Saito *et al.*, QMC 1999 (*op cit*)

Data: Morgenstern & Meziani

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

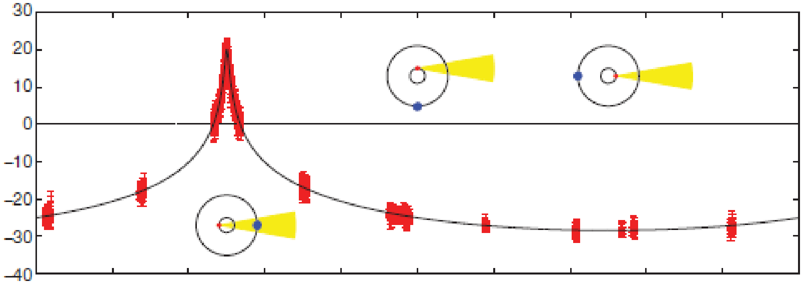
Neutron Stars

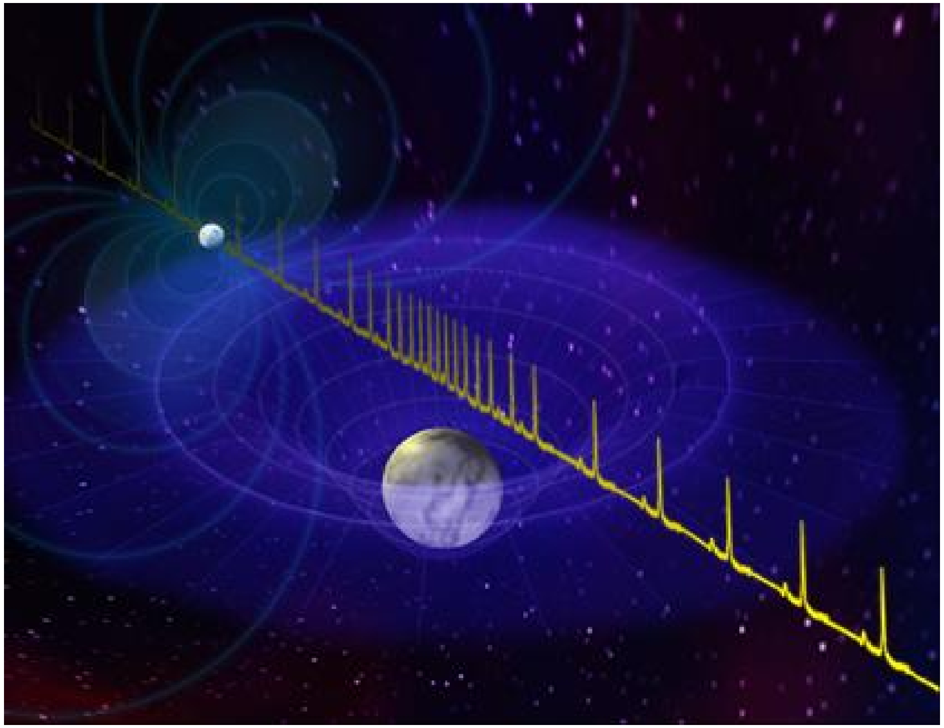
LETTER **(2010)**

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

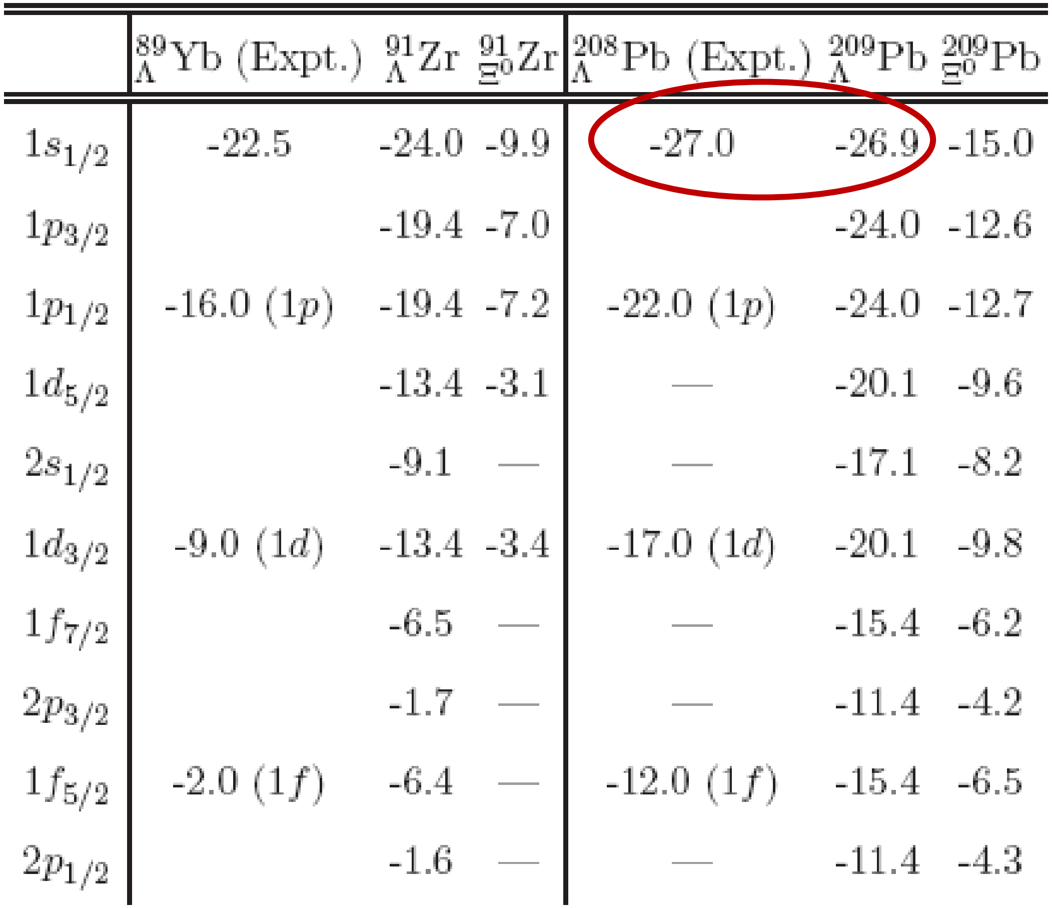
- Attractive and repulsive forces (σ and ω mean fields) both decrease as # light quarks decreases

- 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



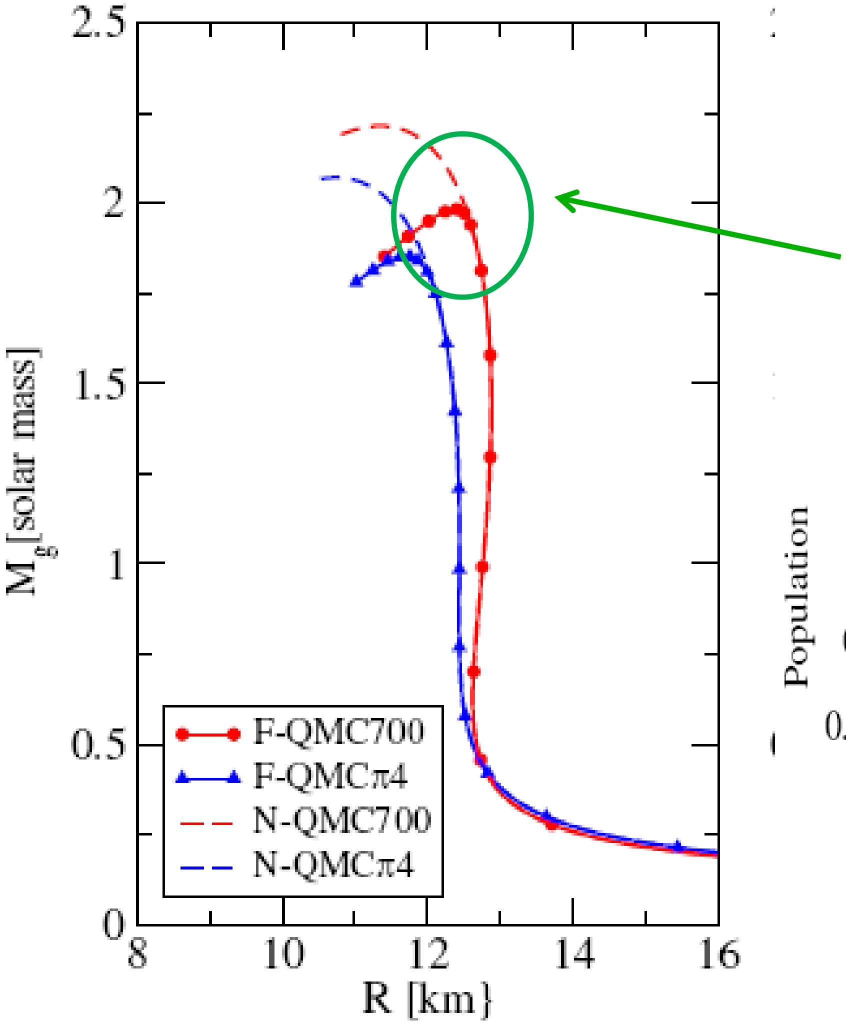
	$^{89}_{\Lambda}$Yb (Expt.)	$^{91}_{\Lambda}$Zr	$^{91}_{\Xi^0}$Zr	$^{208}_{\Lambda}$Pb (Expt.)	$^{209}_{\Lambda}$Pb	$^{209}_{\Xi^0}$Pb
$1s_{1/2}$	-22.5	-24.0	-9.9	-27.0	-26.9	-15.0
$1p_{3/2}$		-19.4	-7.0		-24.0	-12.6
$1p_{1/2}$	-16.0 ($1p$)	-19.4	-7.2	-22.0 ($1p$)	-24.0	-12.7
$1d_{5/2}$		-13.4	-3.1	—	-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 10-15 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)

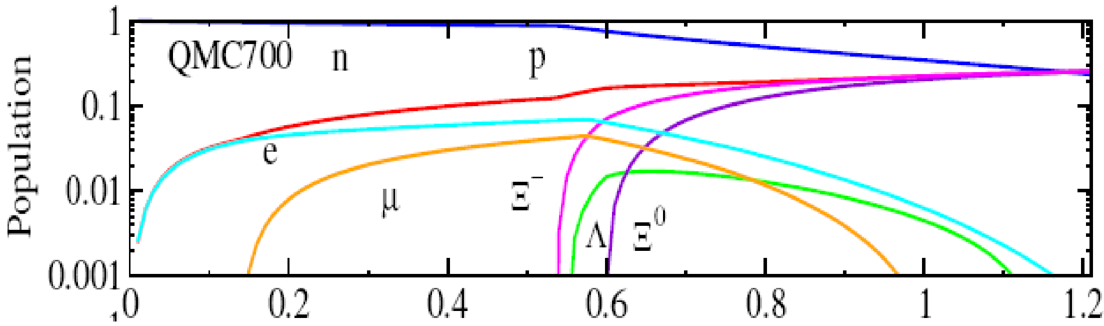
Guichon *et al*., Nucl.Phys. A814 (2008) 66; see also 1998

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.....

Just for fun….

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

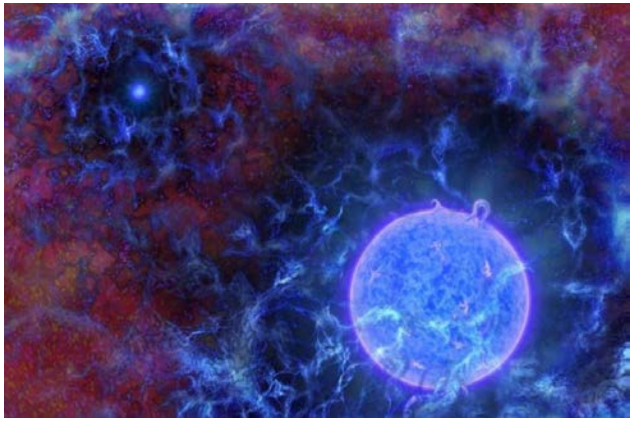
$$\mathbf{n} \longrightarrow \text{Dark Matter } (\chi) + \text{something}$$

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

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

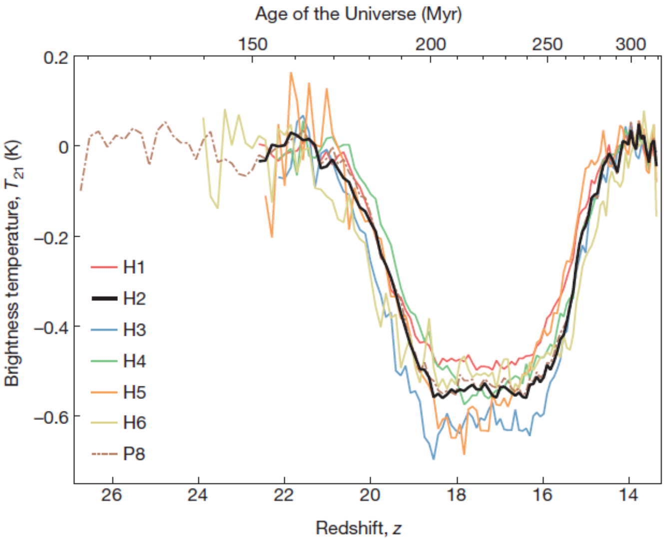
Astronomers detect signal from the dawn of the universe, using simple antenna in WA outback



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

  mass < few GeV

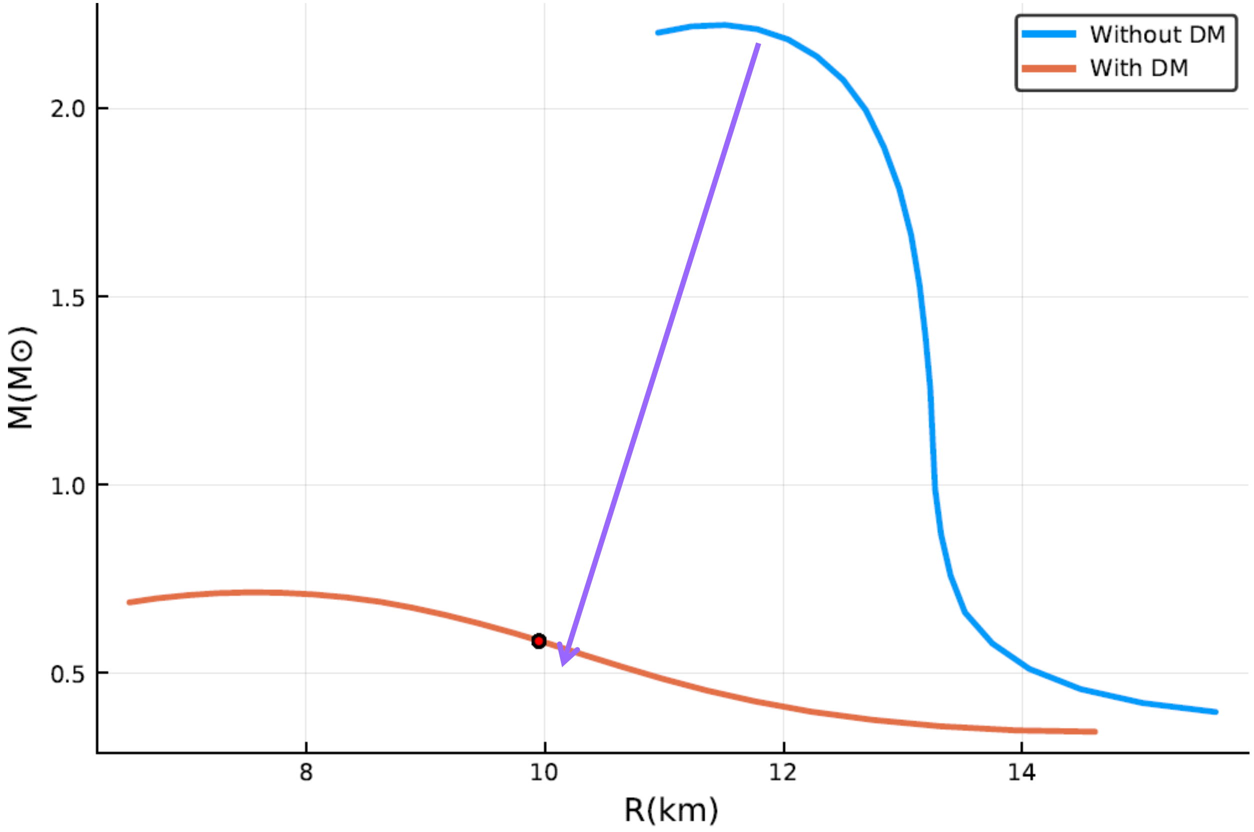
  and $\sigma > 10^{-21}$ cm^2



Solve Tolman-Oppenheimer-Volkoff Equations

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

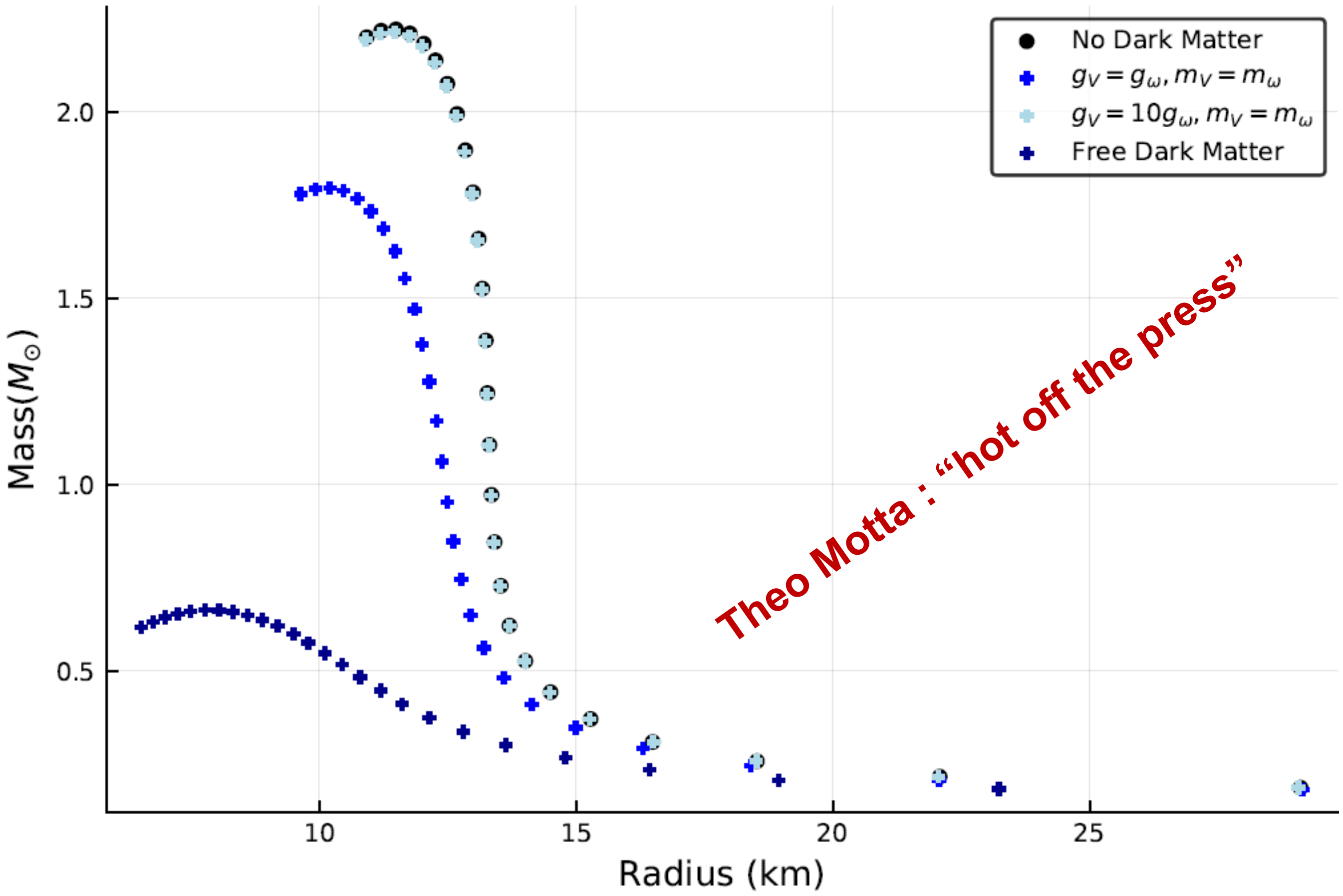
- **But cannot even get that as maximum stable star goes to just 0.58 $M_\odot$**



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

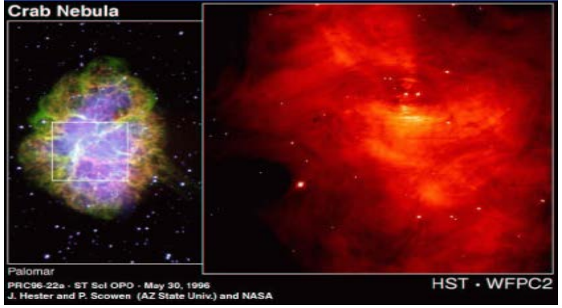
Is there a way out?

- **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**



Theo Motta : “hot off the press”

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 $2M_{\odot}$ *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

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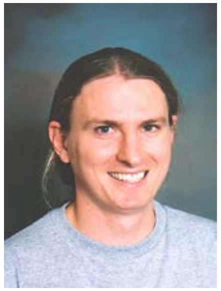
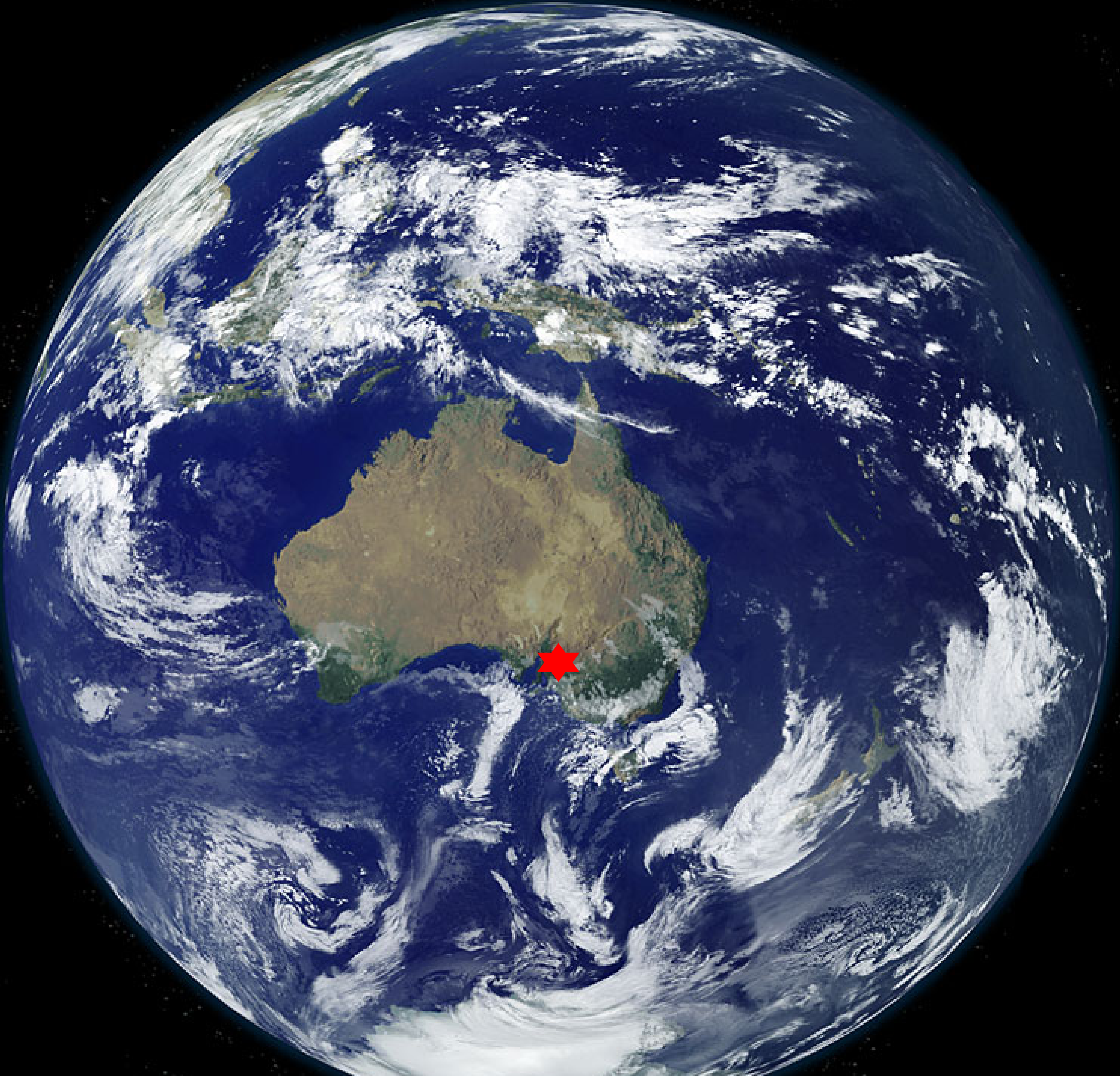

Cloët


Whittenbury


Simenel


Martinez


Motta



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**

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**

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 <u>chiral invariant</u> 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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