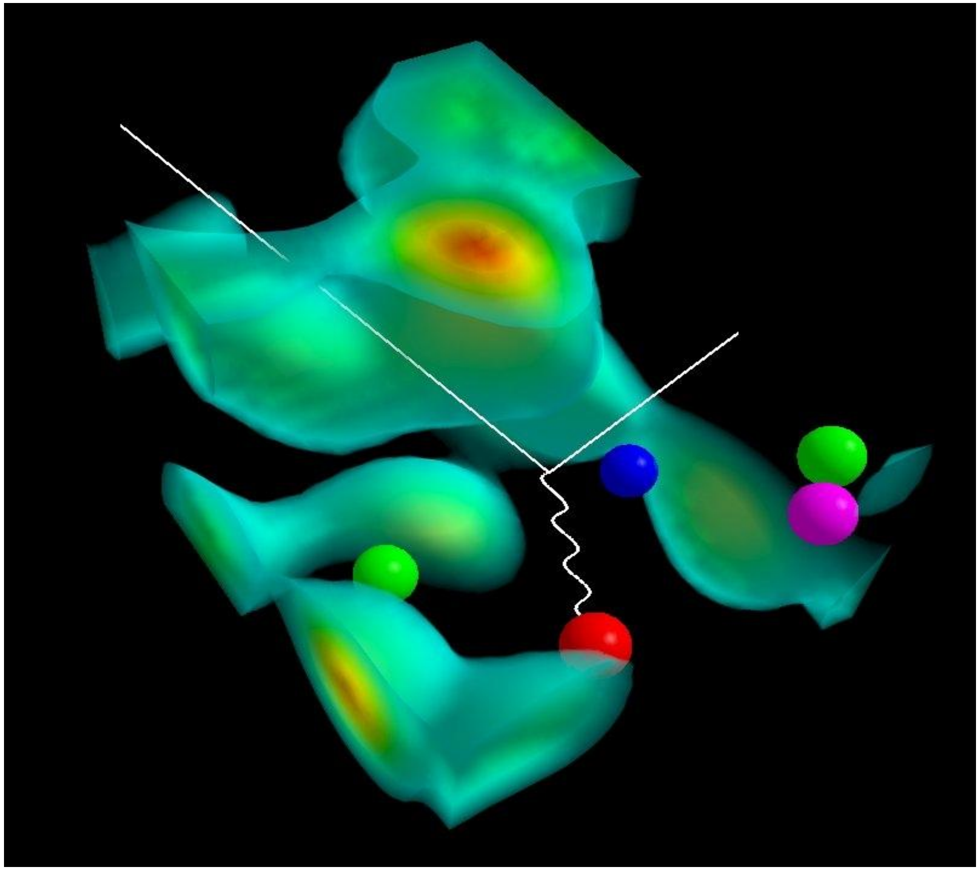
Structure of Finite Nuclei Starting at the Quark Level



Anthony W. Thomas

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Australian Government
Australian Research Council

INPC2016
Adelaide : 12th September 2016

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SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Outline

- Start from a QCD-inspired model of *hadron* structure
- Ask how that internal structure is modified in-medium
- This naturally leads to saturation
  + predictions for all hadrons (e.g. hypernuclei...)
- Derive effective forces (Skyrme type): apply to finite nuclei
- Test predictions for quantities sensitive to internal structure: DIS structure functions, form factors in-medium....

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11 – 16 September 2016
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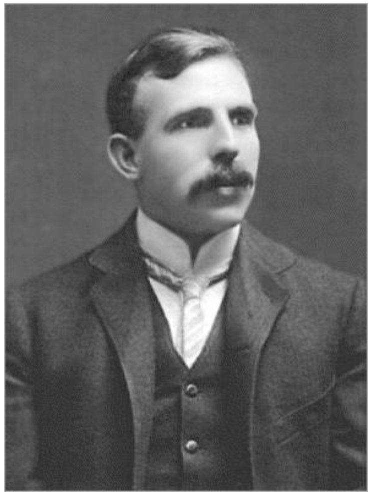
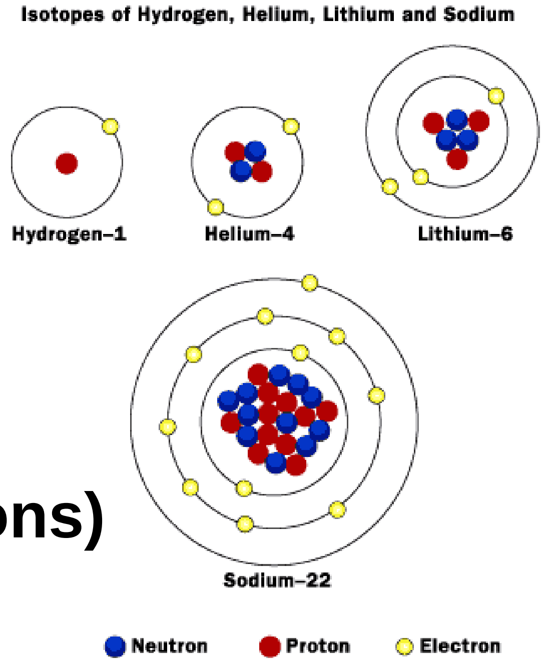
Rutherford



Discovered that alpha particles went straight through matter – most of the time

Occasionally scatter very hard
– back the way they came!

Concluded matter is mainly empty space!



There is a heavy nucleus surrounded
at a (comparatively great distance by electrons)

- **Since the neutron was discovered by Chadwick, nuclei have been built from neutrons and protons*, with exactly the same properties in-medium as outside*, interacting through the exchange of pions and other mesons**

- **BUT is that the whole story?**

- **After all, along came QCD in the 1970s!**

BUT regarded as irrelevant to nuclear structure............

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."

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Fundamental Question for Nuclear Physics

- **Is the nucleon IMMUTABLE ?**

- **i.e. When immersed in a nuclear medium with *applied scalar field strength of order half its mass* is it really unchanged??**

- **When looked at in the context of QCD as the theory of the strong force clearly NO**

- **Is this irrelevant to nuclear structure? NO**

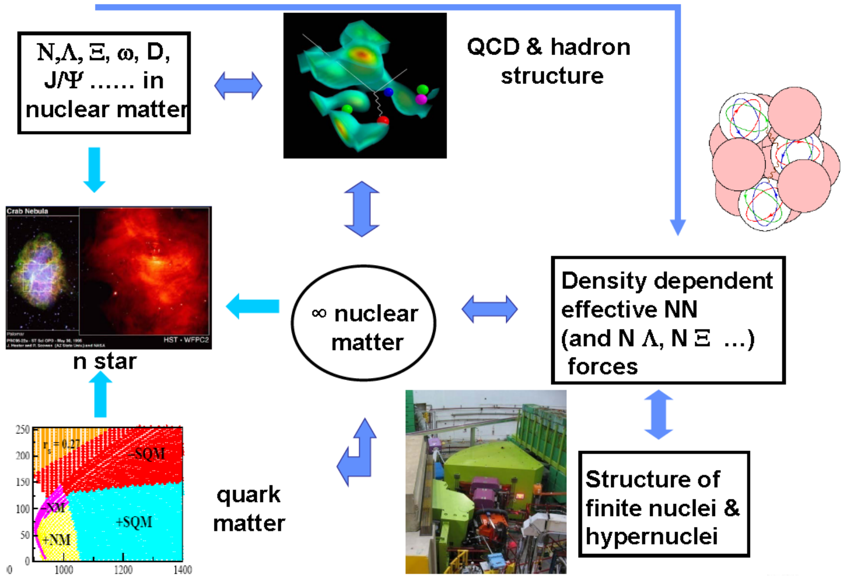
- **Indeed, we argue it is of fundamental importance.....**

A different approach : QMC Model

(Guichon, Saito, Tsushima et al., Rodionov et al.
- see Saito et al., Progress Part. Nucl. Phys. 58 (2007) 1 for a review)

- **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> $g^q_{\sigma,\omega,\rho}$**
  - **determine by fitting to saturation properties of nuclear matter (ρ_0 , E/A and symmetry energy)**

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

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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

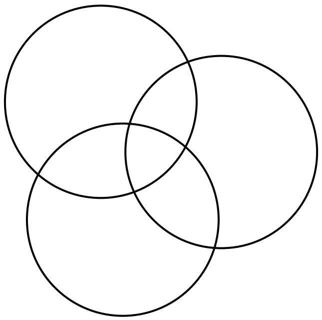
$$M^*(\vec{R}) = M - g_\sigma \sigma(\vec{R}) + \frac{d}{2}\left(g_\sigma \sigma(\vec{R})\right)^2$$

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

Indeed, in nuclear matter at mean-field level (e.g. QMC), 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:**

– **scalar polarizability is natural source of 3-body force**

Finite nuclei

Derivation of Density Dependent Effective Force

Physical origin of density dependent forces of Skyrme type within the quark meson coupling model

P.A.M. Guichon [a,*], H.H. Matevosyan [b,c], N. Sandulescu [a,d,e], A.W. Thomas [b]

Nuclear Physics A 772 (2006) 1–19

- **Start with classical theory of MIT-bag nucleons with structure modified in medium to give M_{eff} (σ).**

- **Quantise nucleon motion (non-relativistic), expand in powers of derivatives**

- **Derive equivalent, local energy functional:**

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

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 Study of Finite Nuclei

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 ($g_\sigma{}^q$, $g_\omega{}^q$, $g_\rho{}^q$) 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)

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			

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) 092501

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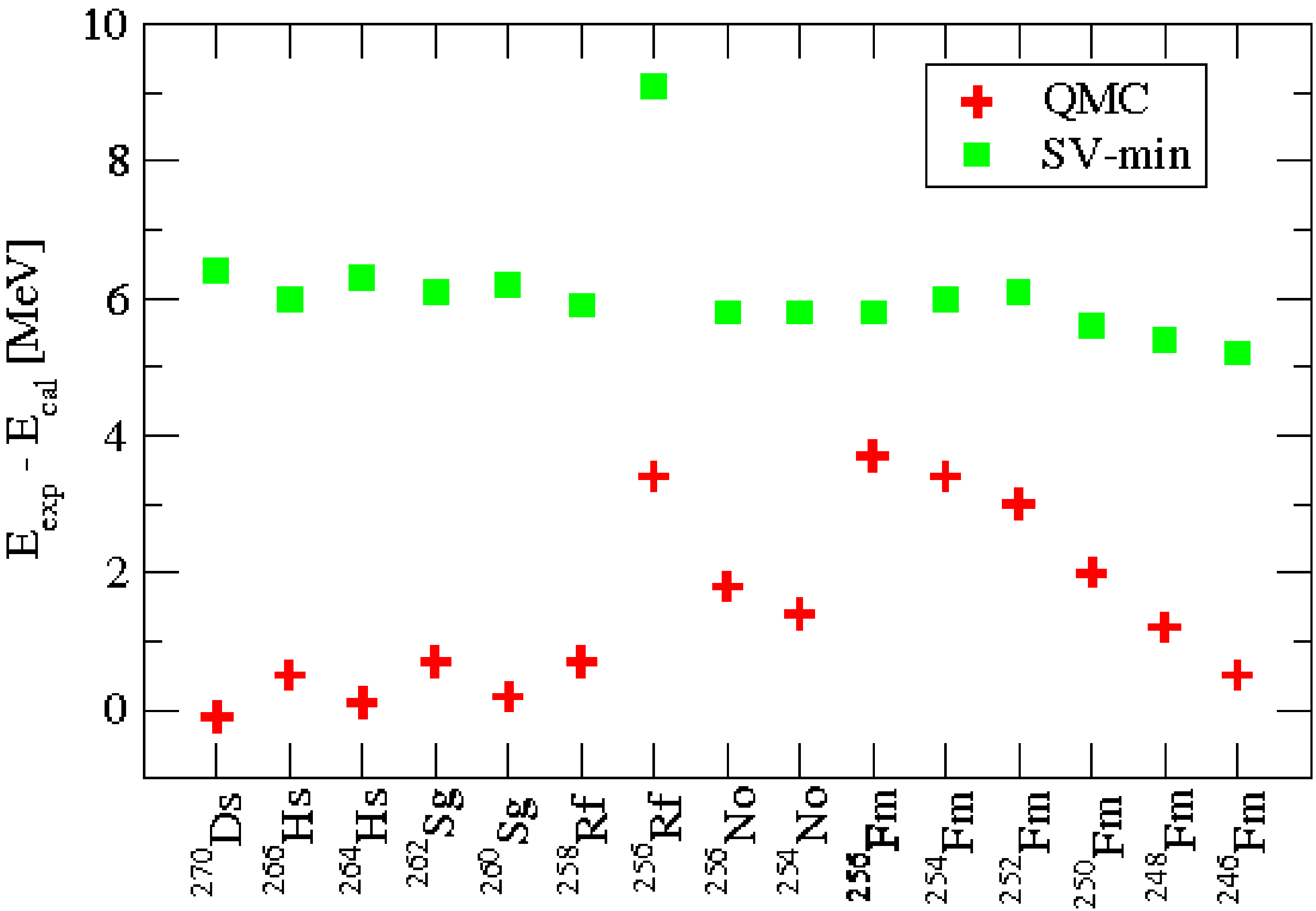
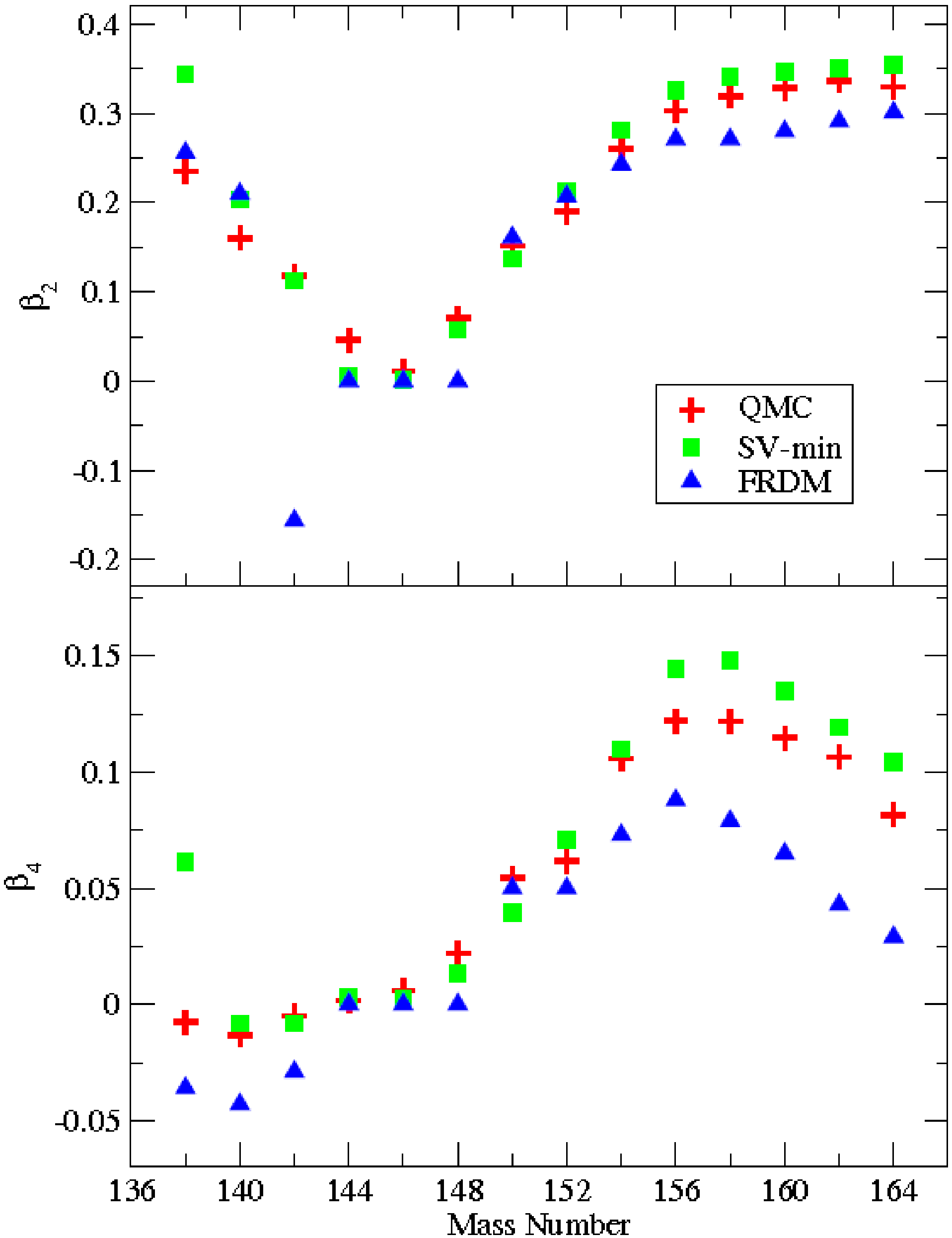
Superheavies : 0.1% accuracy



Stone et al., PRL (2016) 092501

Deformation in Gd (Z=64) Isotopes



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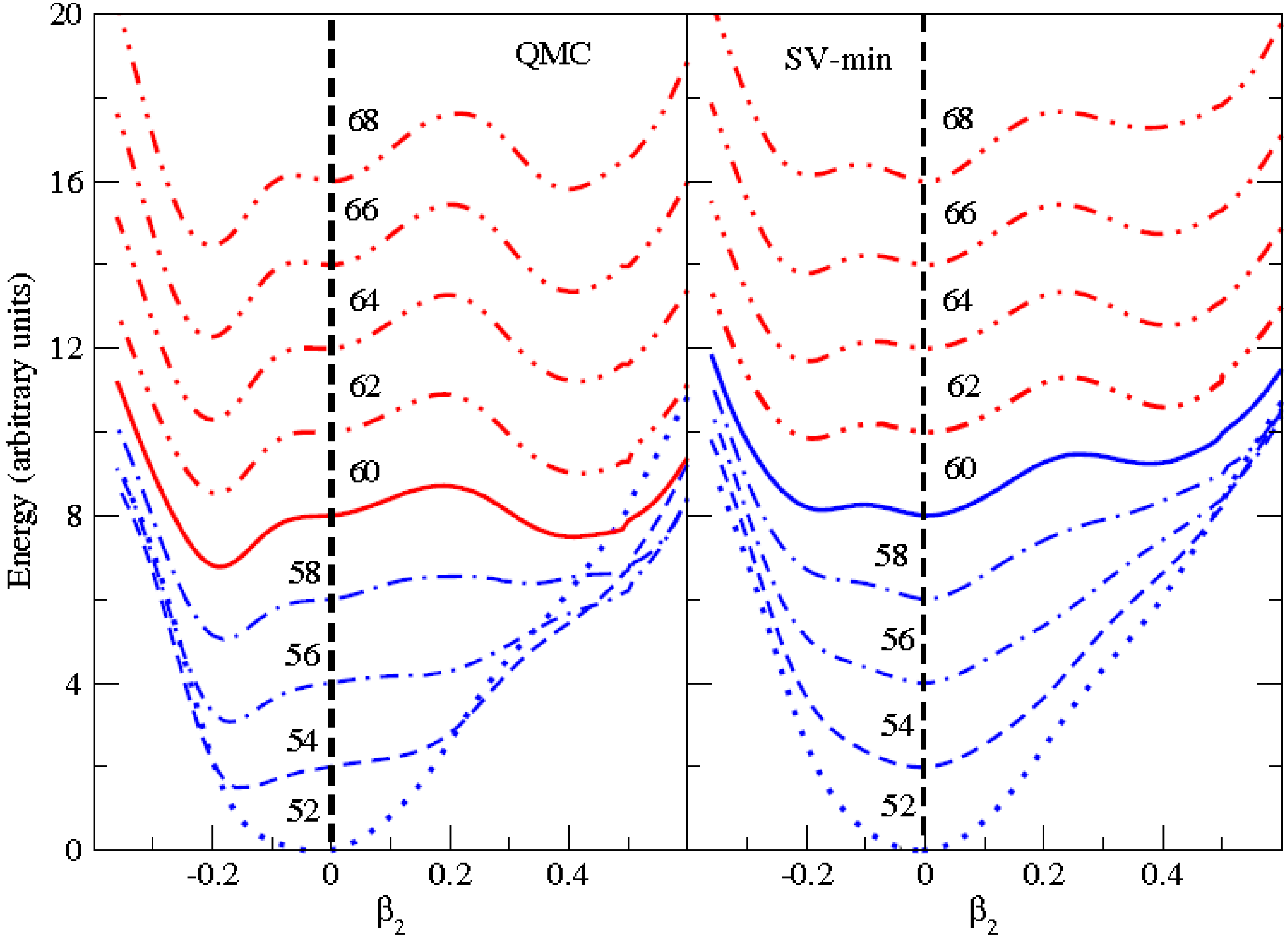
Spin-orbit splitting

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

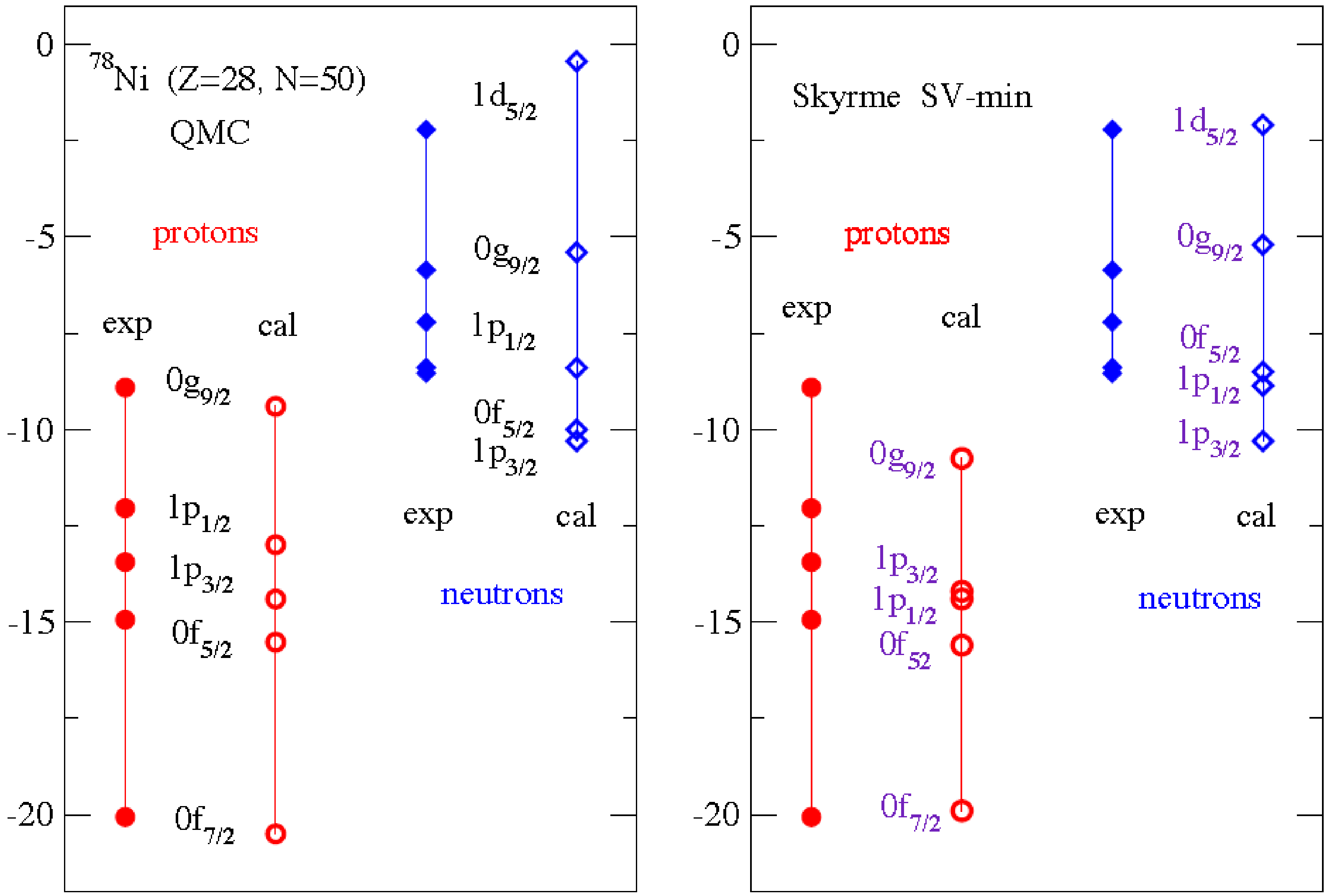
Shape evolution of Zr (Z=40) Isotopes



- **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 (2016) 092501

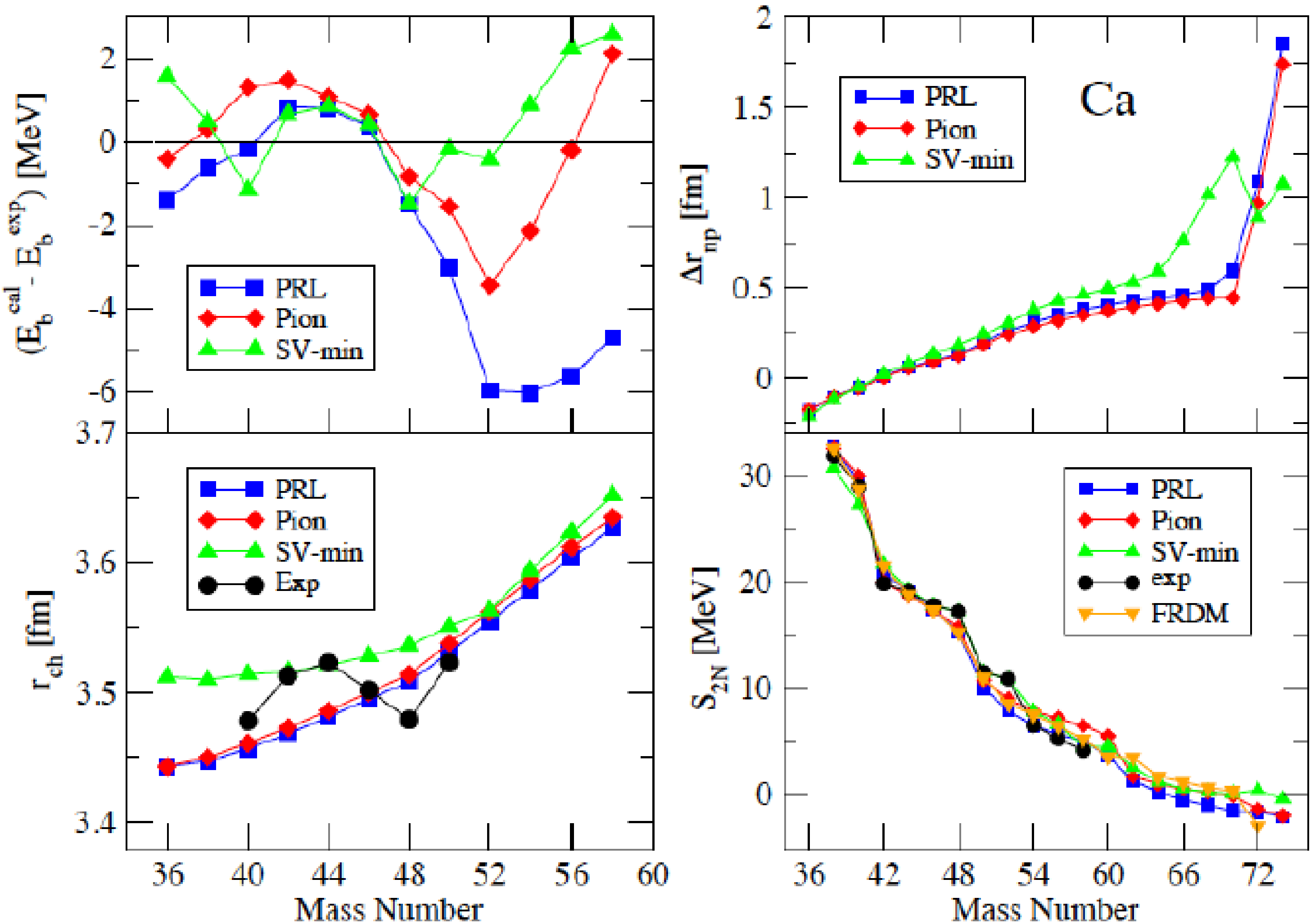
"Hot off the press"



Traditionally very hard to describe

Addition of pion – effect in Ca region

Pion Fock term does improve binding away from stability



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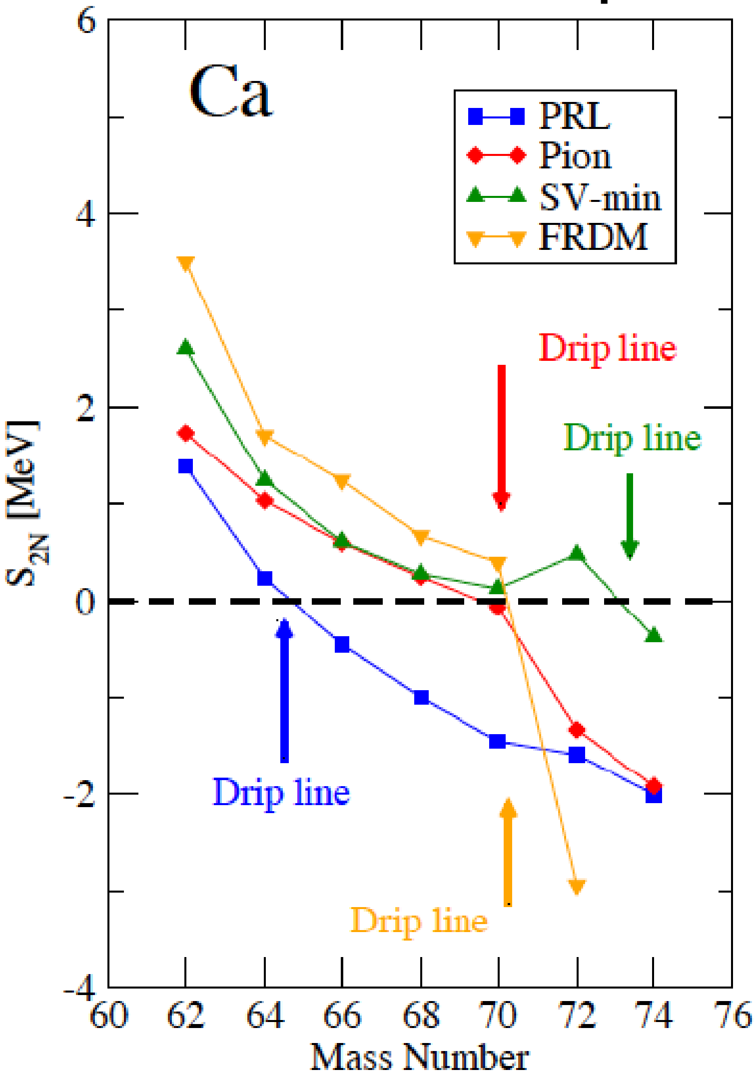
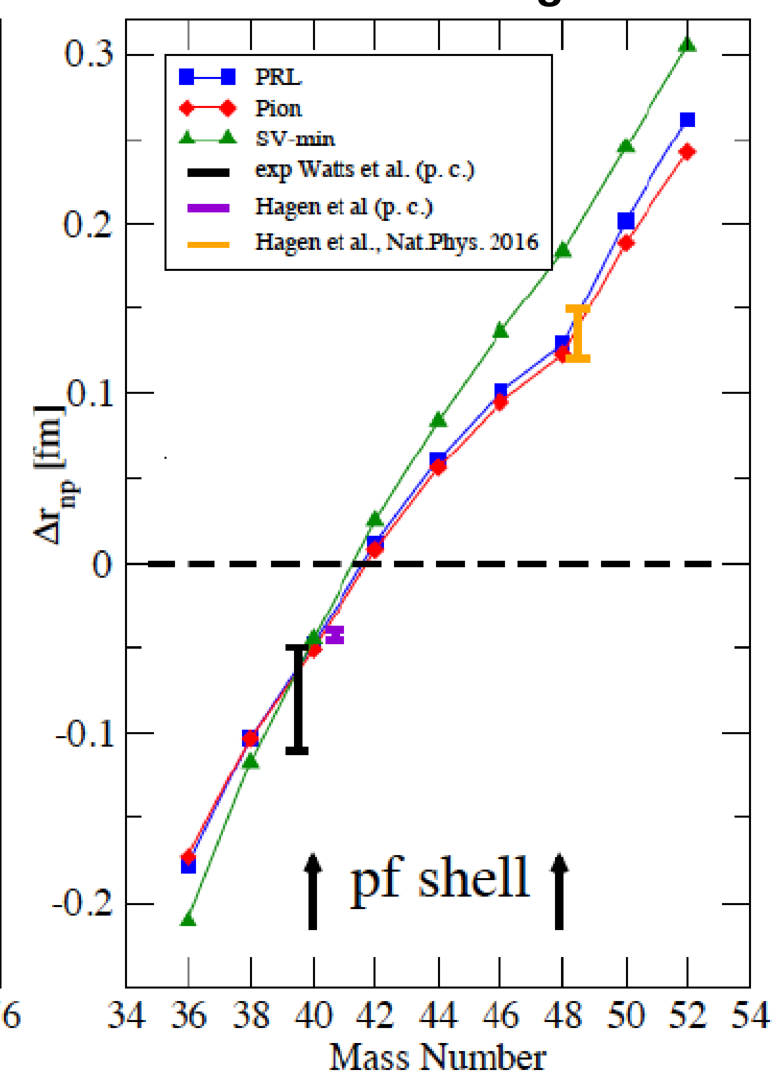
More on addition of pion

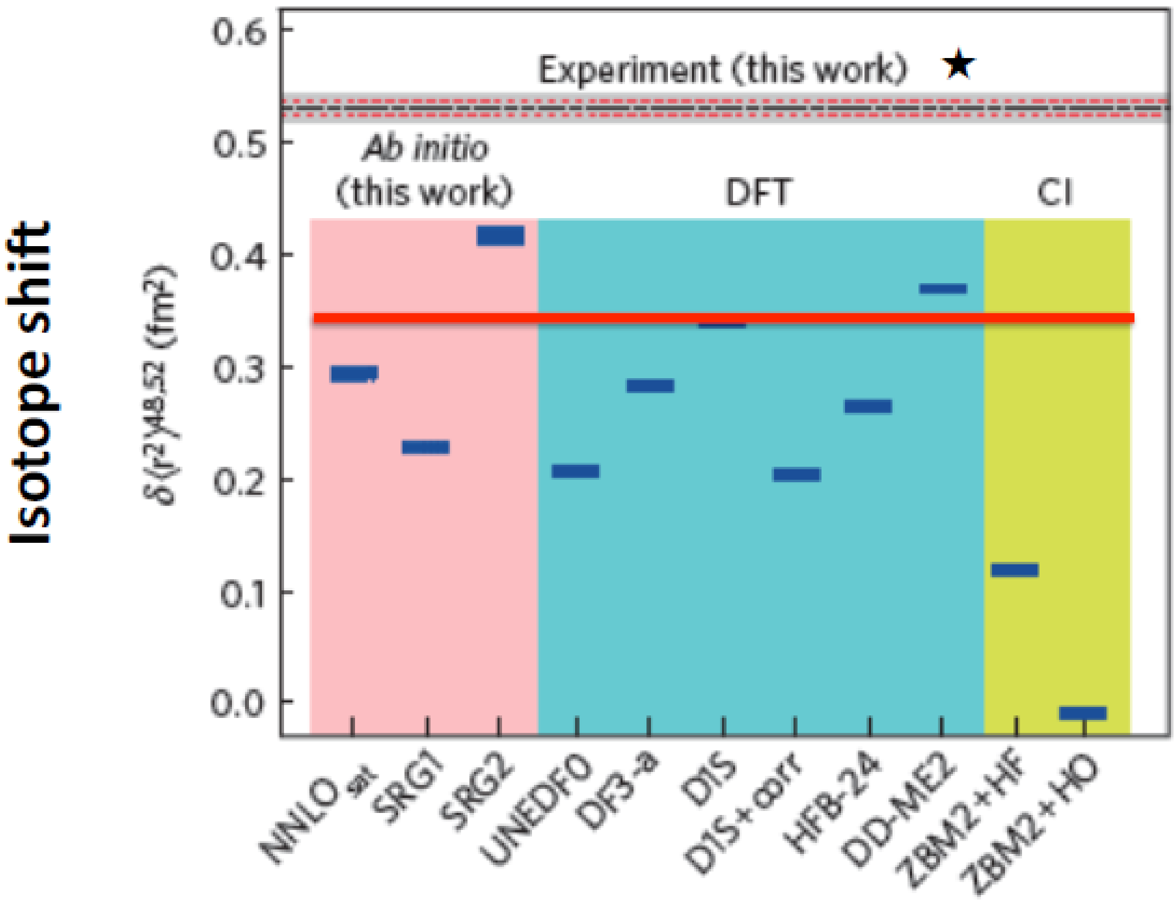
Closer look near drip line



n-skin of 48Ca good



Sudden size increase above ^{48}Ca



$\delta < r_{ch}^2 >^{48,52}$

0.530(5) fm^2 exp
0.340 fm^2 QMC(π)
0.192 fm^2 SV-min

$\delta < r_{ch}^2 >^{48,50}$

0.293(37) fm^2 exp
0.169 fm^2 QMC(π)
0.107 fm^2 SV-min

★ Garcia Ruiz et al., Nat. Phys. 12, 594 (2016)

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......**

Nuclear DIS Structure Functions

To address questions like this one MUST start with a theory that quantitatively describes nuclear structure – very, very few examples.....

EMC Calculations for Finite Nuclei

(Spin dependent EMC effect TWICE as large as unpolarized)

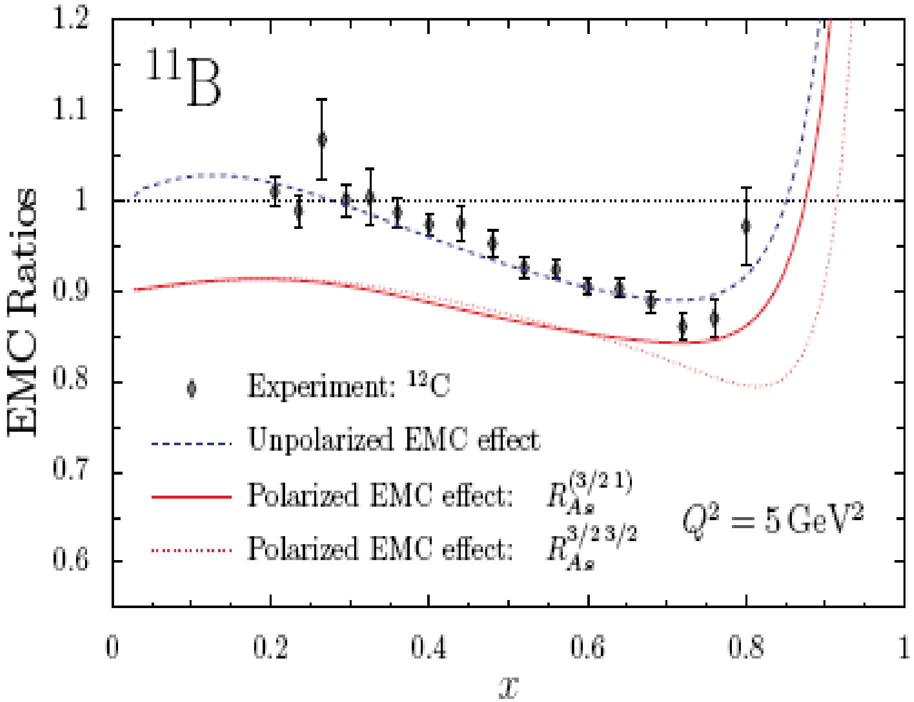


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

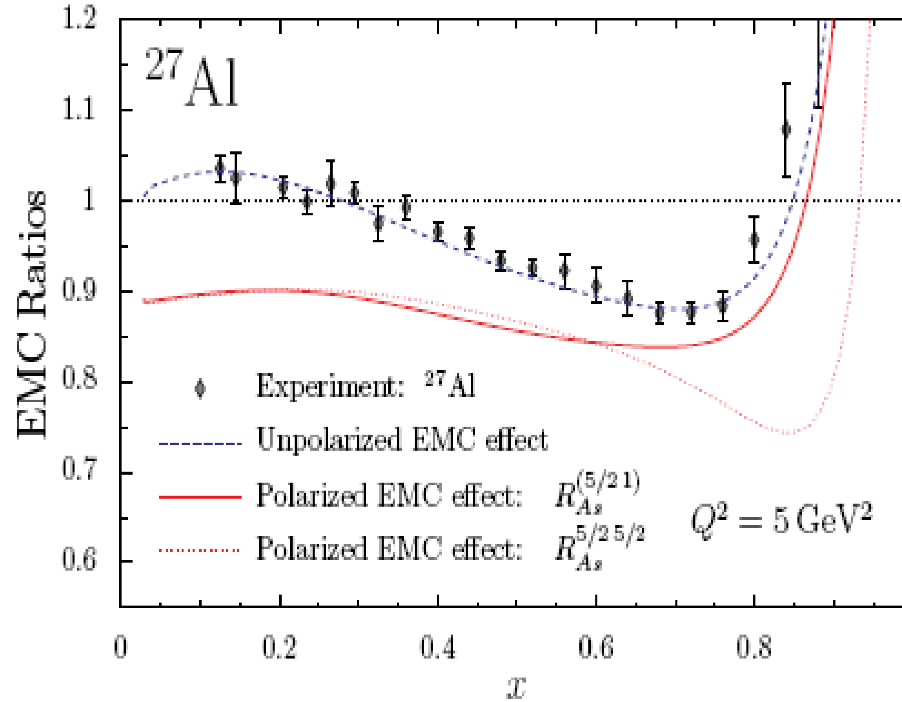


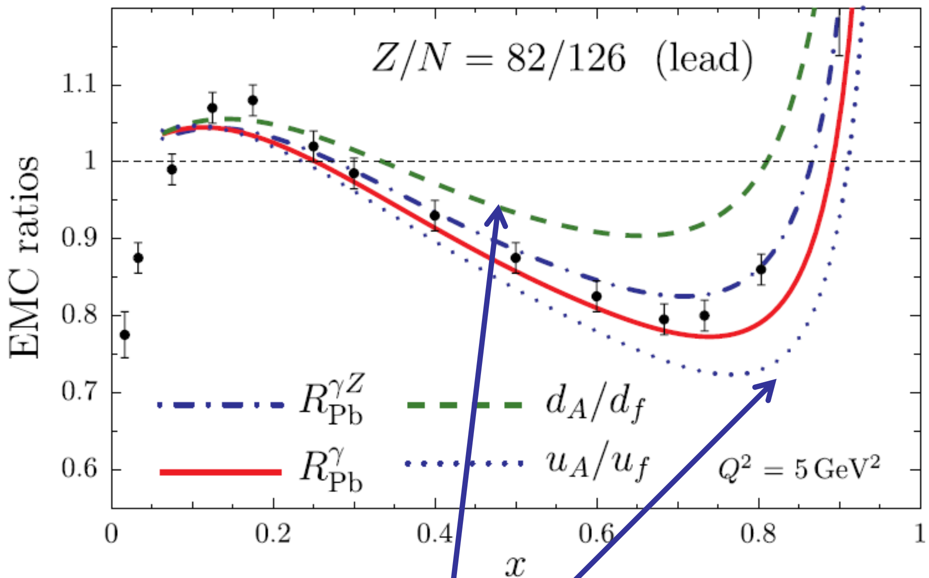
FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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

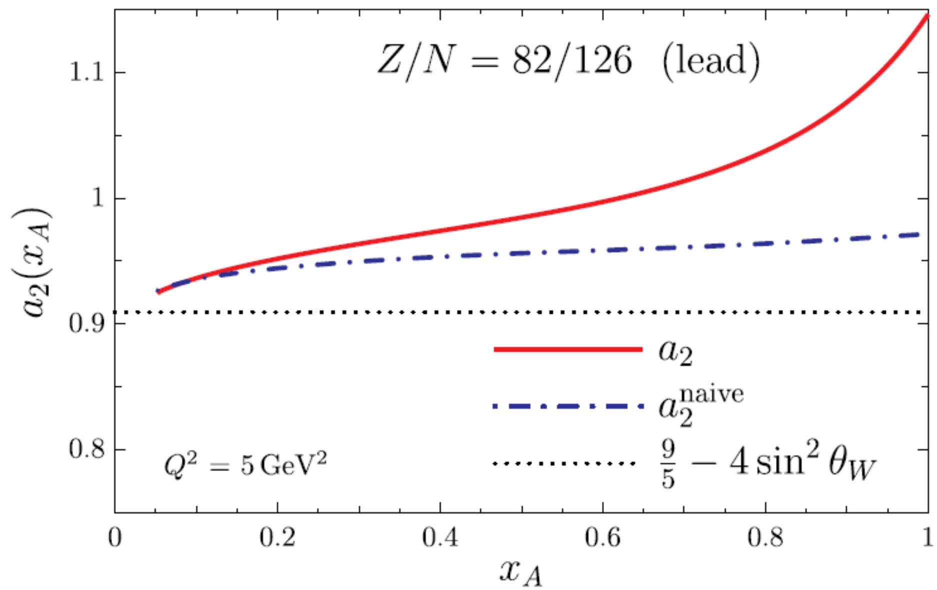
PRL **109**, 182301 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

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]



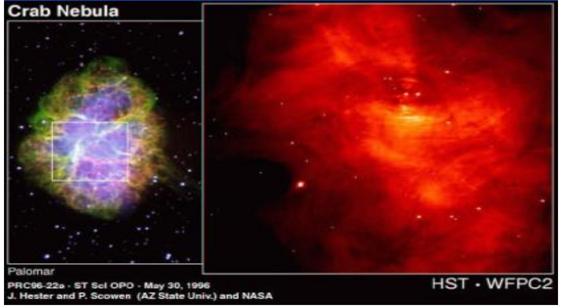
$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{em}}\left[a_2(x_A) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x_A)\right]$$



Ideally tested at EIC with CC reactions

Parity violating EMC will test this at JLab 12 GeV

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 force/ density dependence of effective forces
  - − clear physical interpretation

- Derived, density-dependent effective force gives results better than most phenomenological Skyrme forces

Summary

- Initial systematic study of finite nuclei very promising
  - Binding energies typically within 0.3% across periodic table

- Super-heavies (Z > 100) especially good
  (average difference 0.1%)

- Deformation, spin-orbit splitting and charge distributions all look good)

- BUT need empirical confirmation:
  - Response Functions & Coulomb sum rule (soon)
  - Isovector EMC effect; spin EMC
  - Your idea here.......................

Special Mentions……

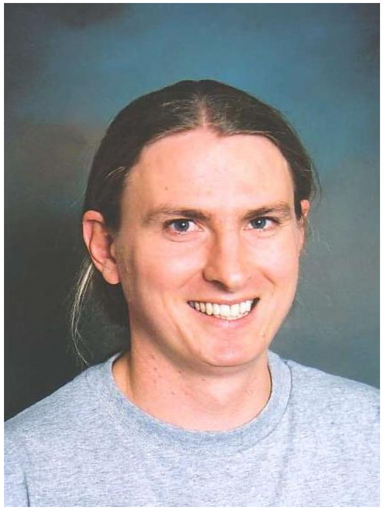
Guichon

Tsushima

Saito

Stone

Bentz



Cloët

Whittenbury

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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

Most recent studies

- Whittenbury, Carrillo-Serrano & Thomas, arXiv: 1606.03158
- Whittenbury, Matevosyan & Thomas, Phys. Rev. C93 (2016) 035807
- Whittenbury, Carroll, Thomas, Tsushima and Stone, Phys. Rev. C89 (2014) 065801

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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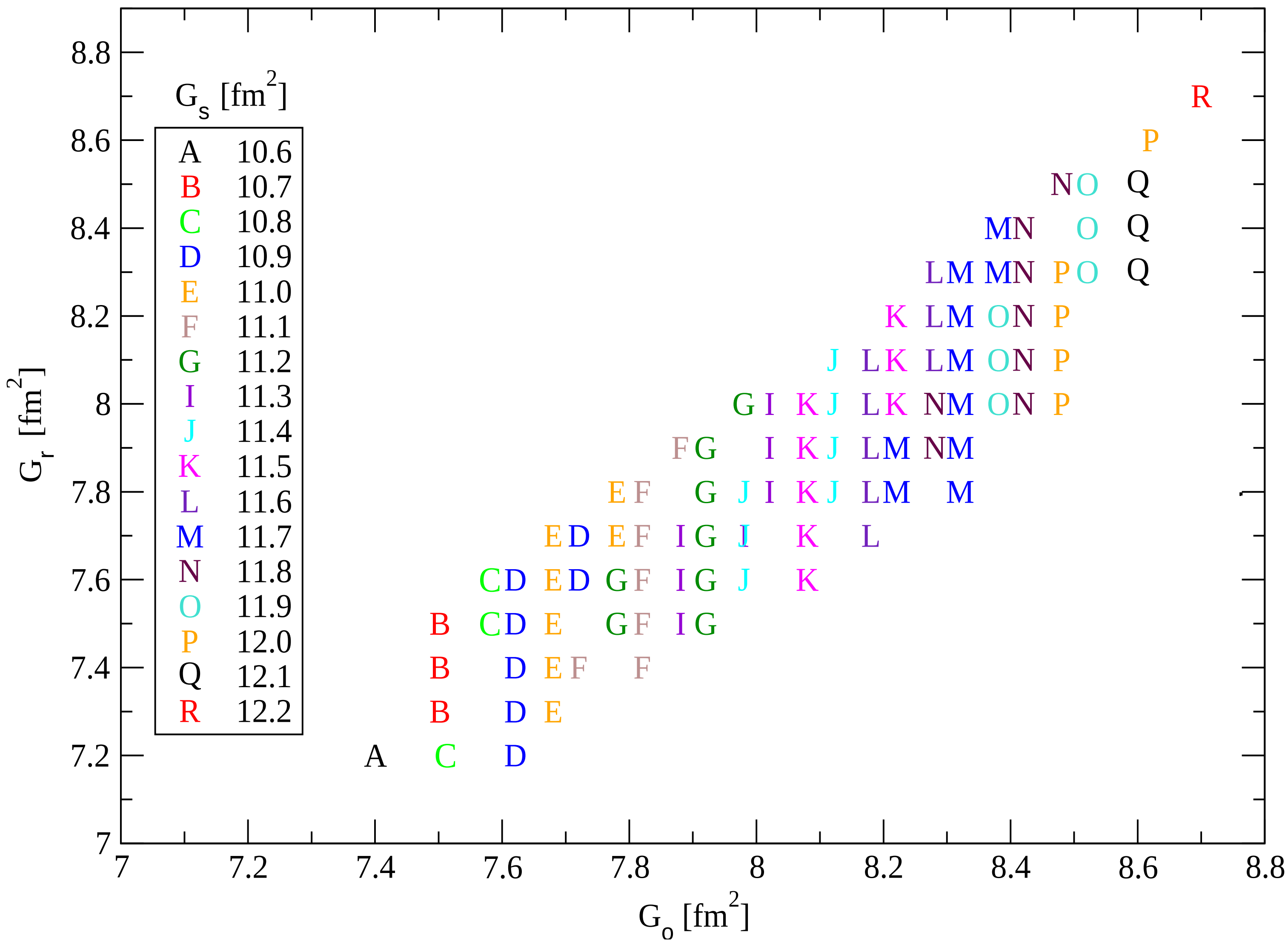
Constraints from nuclear matter



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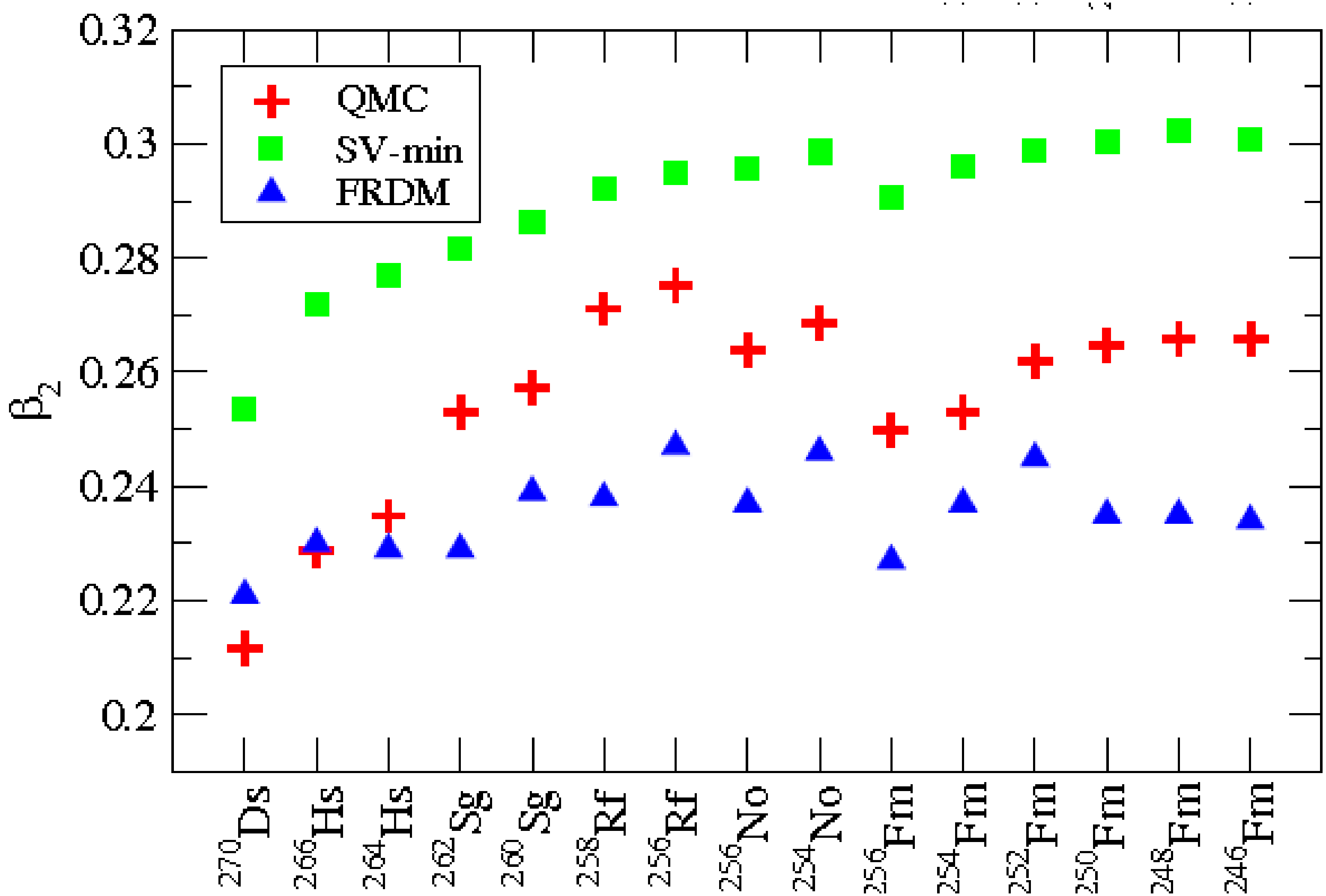
Quadrupole Deformation of Superheavies



Stone et al., PRL (2016)