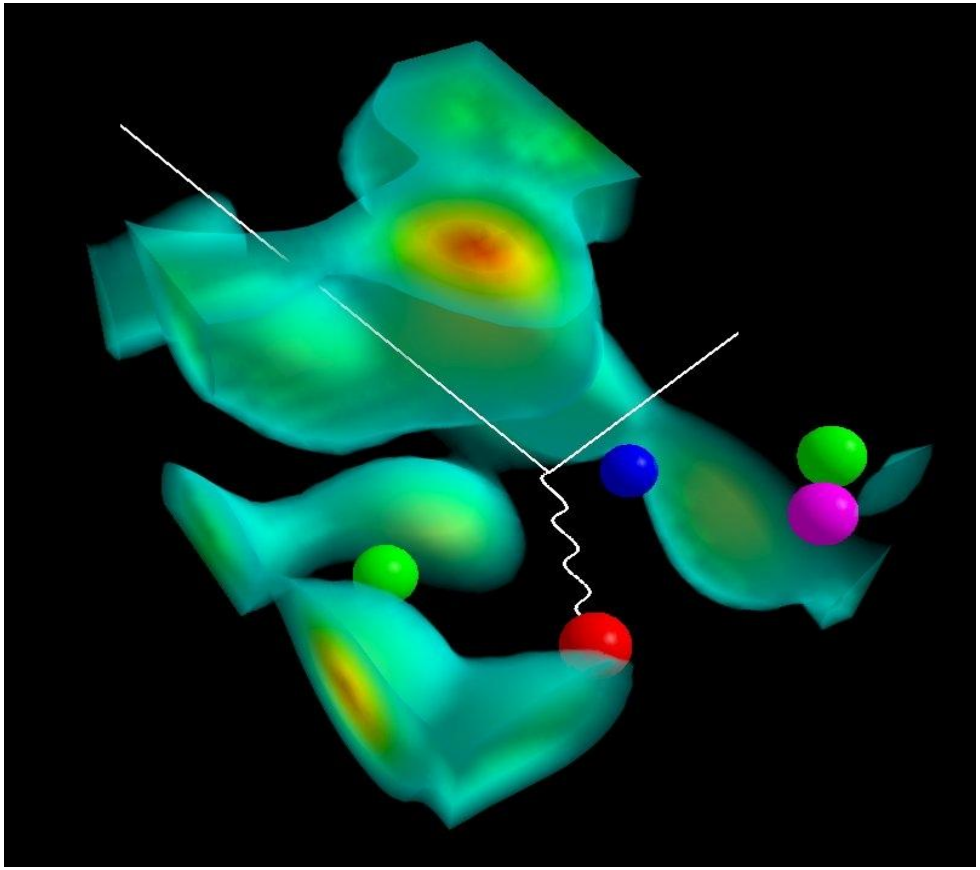
QCD and a New Paradigm for Nuclear Structure



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Anthony W. Thomas

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New Directions in Subatomic Physics
Adelaide : March 10th 2016

QCD and a New Paradigm for Nuclear Structure

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New Directions in Subatomic Physics
In Honour of Tony Williams

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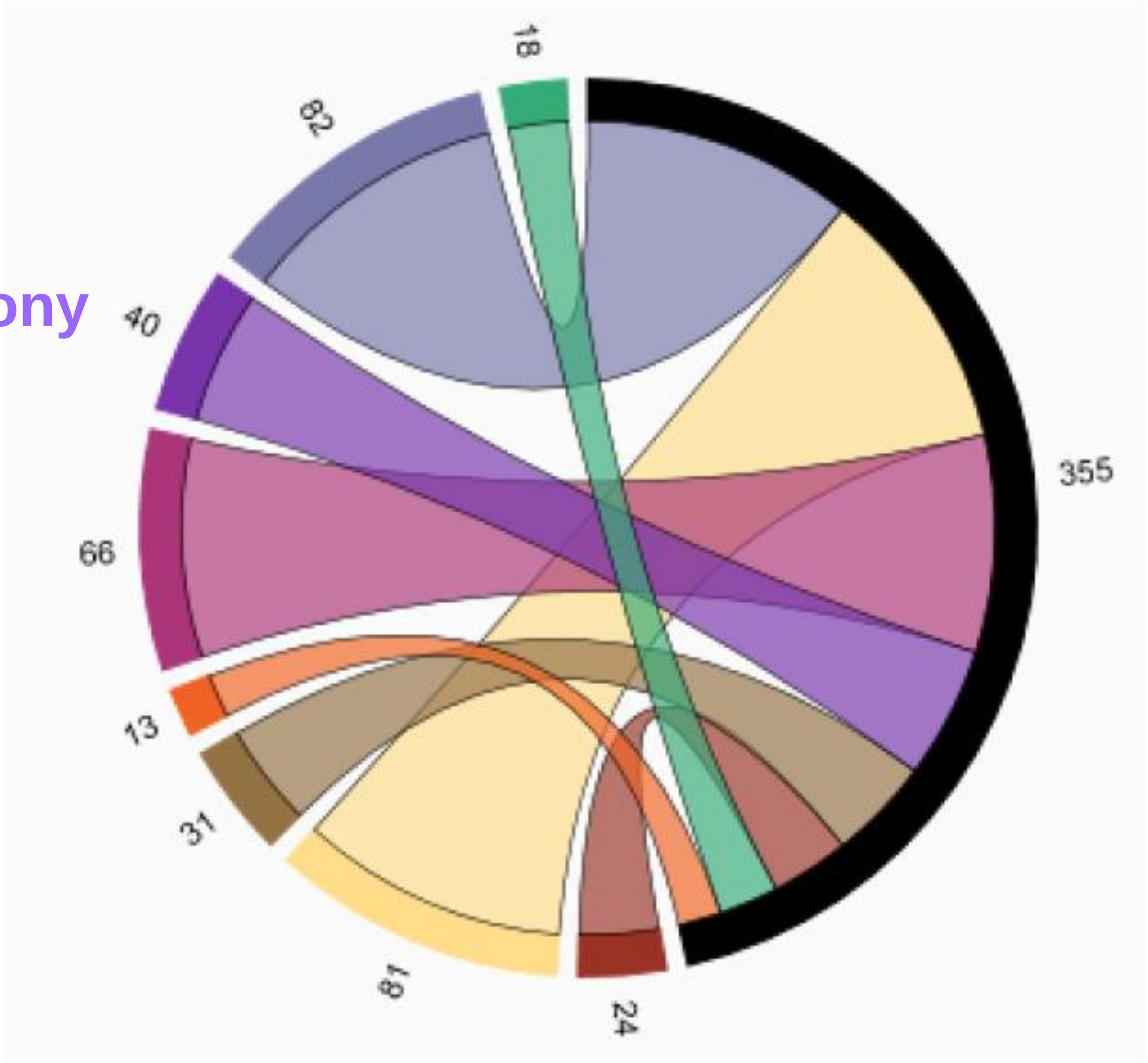
More than 50 joint publications 1985+

Tony



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Physics Department 1986

Physics Department 1986

Governor Eric Neil at NITP

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The path to CSSM and CoEPP : 1995

Japan-Australia Workshop 1995

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STRUCTURE OF MATTER

Tony Williams

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

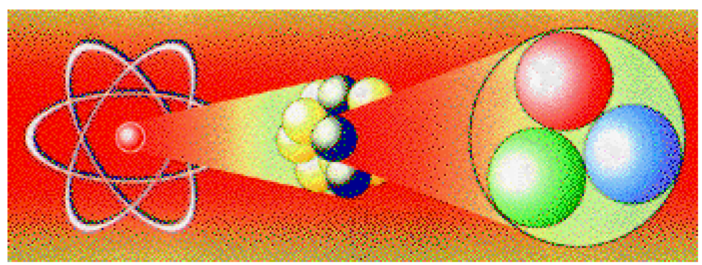
CSSM

Derek Leinweber

- Centre for the Subatomic Structure of Matter formed as an ARC Special Research Centre in 1997

- To understand the quark structure of matter from protons and neutrons to atomic nuclei and neutron stars (pulsars)

Sharon Johnson



Ramona Adorjan

CoEPP

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SUBATOMIC STRUCTURE OF MATTER

CSSM early this millennium

Who has a new computer?

No Tony but still a good photo

Same Workshop – QCD Down Under

Pacspin 2011

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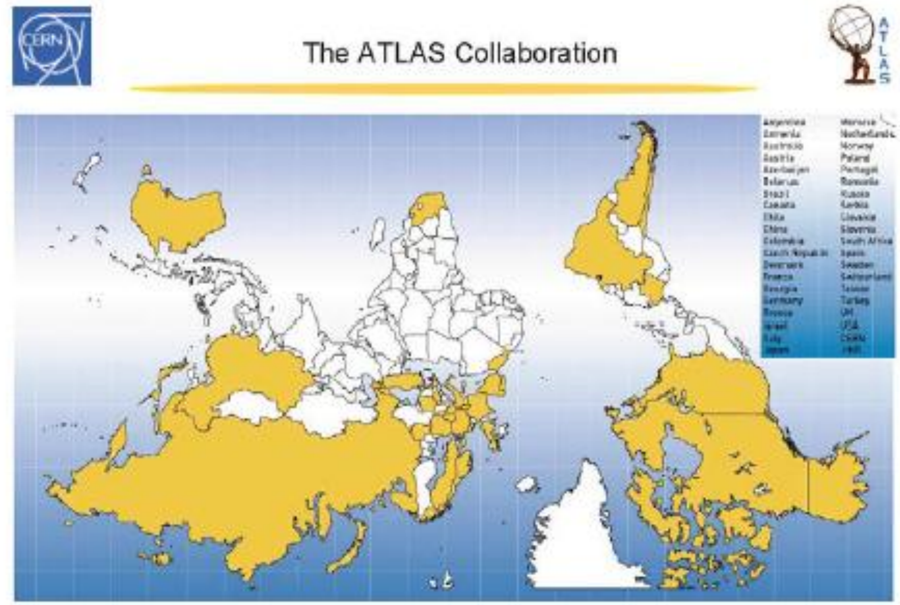
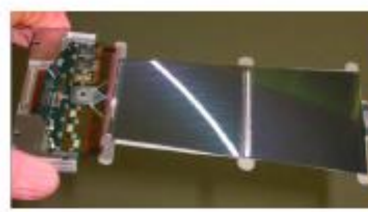
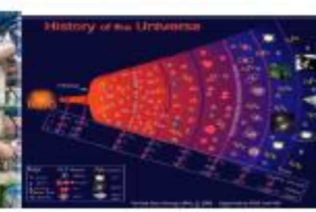
ARC Centre of Excellence for Particle Physics at the Tera-Scale



The University of Adelaide
The University of Melbourne
The University of Sydney
Monash University





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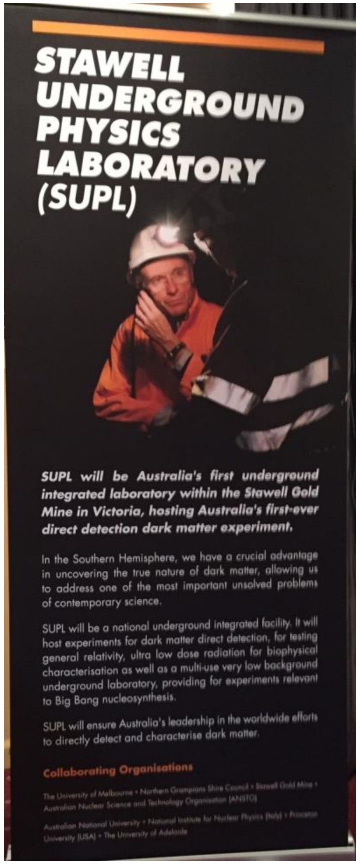
Stawell Underground Physics Laboratory



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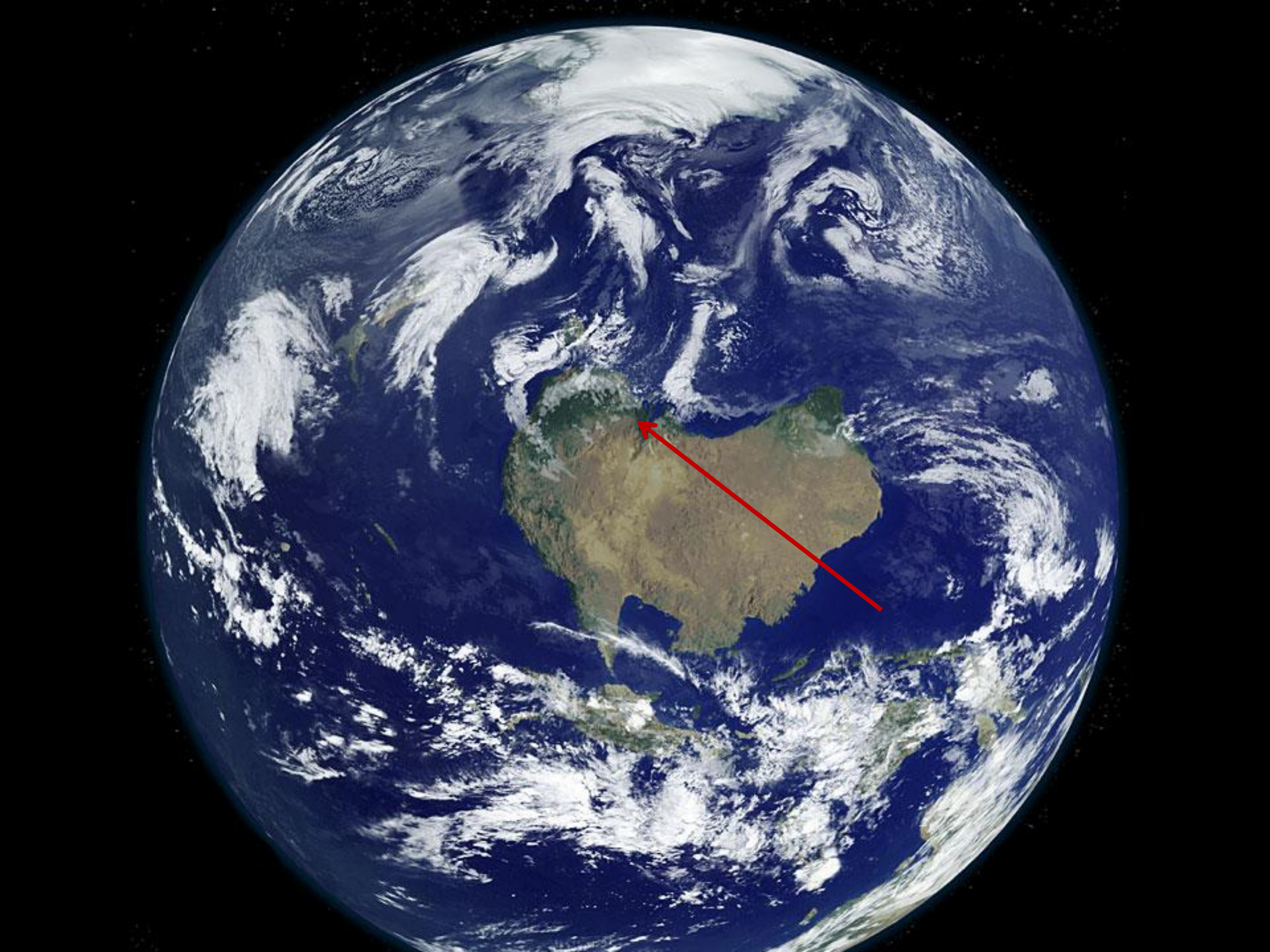


A decade ago.....

PLANS FOR A NATIONAL DUMP DITCHED

July 14, 2004

Photo: South Australian Premier Mike Rann spent years fighting the Federal Government's nuclear waste plans. (ABC News)

The Federal Government abandons its plan to build a single national radioactive waste dump in South Australia.

The Commonwealth wants each state and territory to build its own waste storage site.

The premier, Mr Rann, describes the decision as a great victory.

and now.....

SA nuclear waste dump would deliver $257b

February 16, 2016

Total revenue from a proposed nuclear waste facility in SA would reach $257 billion. *Photo: Glenn Campbell*

Momentum is growing for the construction of a nuclear waste facility in Australia to store and dispose of spent nuclear fuel rods and other waste from around the world in a project which would deliver $257 billion in revenue with signs of a bipartisan approach from the major federal political parties on the issue.

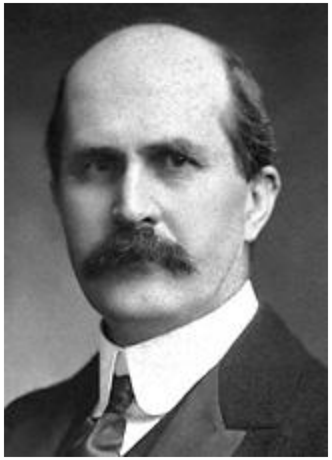
Kevin Scarce, a former South Australian governor who spent almost 12 months taking evidence from 128 witnesses, handed down his preliminary findings on Monday from The Nuclear Fuel Cycle Royal Commission which examined if South Australia should expand from being a uranium miner into enrichment, waste storage and power generation.

Read more: http://www.smh.com.au/business/energy/sa-nuclear-facility-would-deliver-257b-revenue-boost-over-its-lifetime-20160211-gmrcgx.html#ixzz42N6Upyur

So let’s discuss nuclear physics

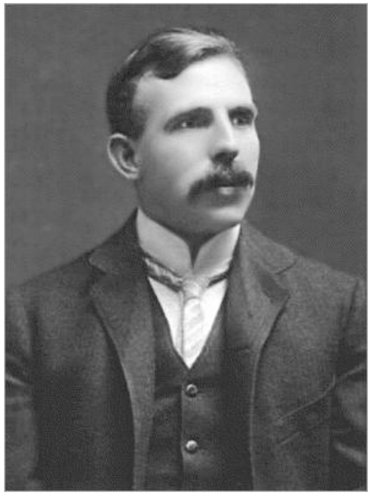
Beginning of the 20th Century

Knew about the proton and the electron − tried to build all atoms from these



In Adelaide William Henry Bragg was trying to understand the nature of X-rays – concluded they were particles

Rutherford



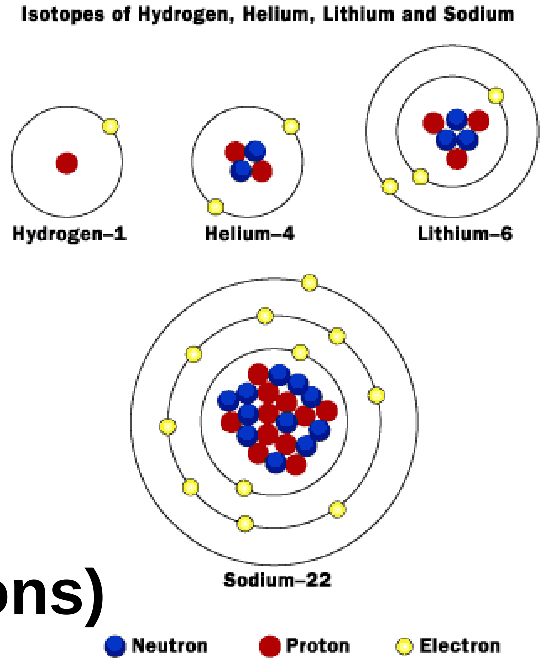
Discovered that alpha particles went

straight through matter – most of the time

Occasionally scatter very hard

– back the way they came!

Concludes matter is mainly empty space!

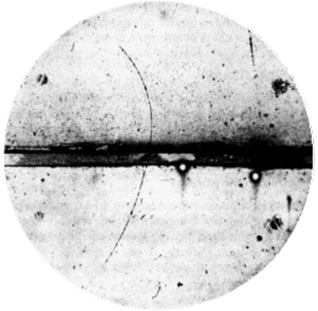


There is a heavy nucleus surrounded

at a (comparatively great distance by electrons)

1930's the Discoveries Accelerate

1932 Chadwick the n ; the positron – or "anti-electron"



Anderson 1933

1940's the muon and pion (predicted by Yukawa in 1935); then in the 50's an "explosion" of new particles – 100's of them generated by new particle accelerators at national or international laboratories

- From that time forward 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 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."

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.....**

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Relativity *really* matters

- **Once we realize that a nucleon has internal structure *the effects of a Lorentz scalar mean field and Lorentz vector mean field are totally different***

- **Of course, they largely cancel to give ~8 MeV binding per nucleon: BUT this is very misleading**

- **Time component of *ω mean field* just shifts the energy scale – *no effect on internal structure***

- **The σ field changes the (very light) quark mass and hence changes the internal dynamics!**

  Strength of the σ field is the real measure of how far off-shell the nucleon is in-medium!

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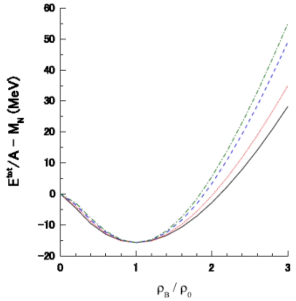
Relevance of QCD to Nuclear Structure



- **Insight into origin of saturation – unexpected!**

- **Behaviour at very high density (neutron star)**
  − transition from hadronic to quark matter

- **EFT *assumes* relevant degrees of freedom (d.o.f):**
  beware lesson of drunk looking for keys under lamp post

  − i.e. EFT has symmetries of QCD ....
  BUT we need to know the relevant d.o.f. too

- **Working at quark level can provide guidance**

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...)

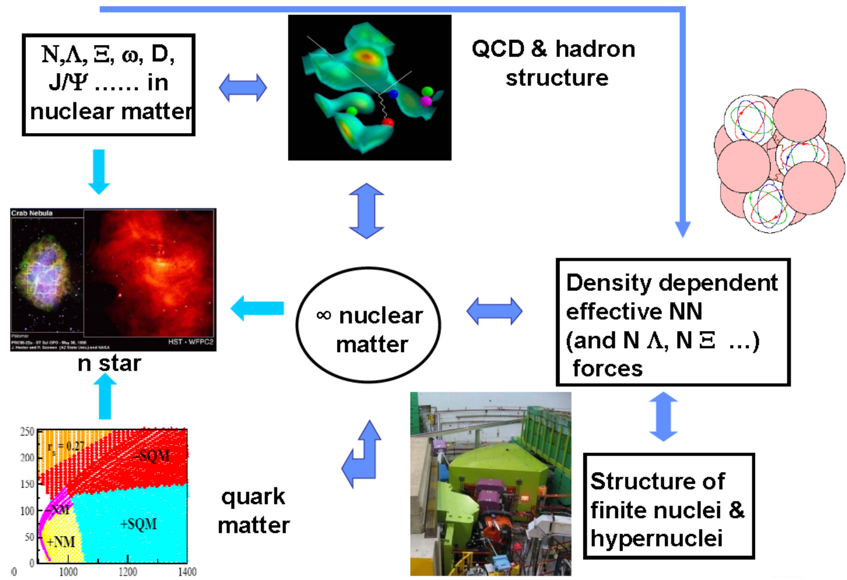
- Derive effective forces (Skyrme type): apply to finite nuclei

- Test predictions for quantities sensitive to internal structure: DIS structure functions, form factors in-medium....

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 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>**
  - **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**

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

- **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***

$$\frac{\Omega_0/2 + m_q^* R_B(\Omega_0 - 1)}{\Omega_0(\Omega_0 - 1) + m_q^* R_B/2}$$

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

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.

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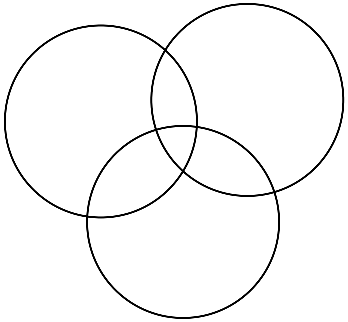
Summary : Scalar Polarizability

- **Can always rewrite non-linear coupling as linear coupling plus non-linear scalar self-coupling – likely physical origin of some non-linear versions of QHD**

- **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

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**

$$
\begin{aligned}
H_{QMC} = & \sum_i \frac{\overleftarrow{\nabla}_i . \overrightarrow{\nabla}_i}{2M} + \frac{G_\sigma}{2M^2} \sum_{i \neq j} \overleftarrow{\nabla}_i \delta(\vec{R}_{ij}) . \overrightarrow{\nabla}_i \\
& + \frac{1}{2} \sum_{i \neq j} \left[\nabla_i^2 \delta(\vec{R}_{ij}) \right] \left[\frac{G_\omega}{m_\omega^2} - \frac{G_\sigma}{m_\sigma^2} + \frac{G_\rho}{m_\rho^2} \frac{\vec{\tau}_i . \vec{\tau}_j}{4} \right] \\
& + \frac{1}{2} \sum_{i \neq j} \delta(\vec{R}_{ij}) \left[G_\omega - G_\sigma + G_\rho \frac{\vec{\tau}_i . \vec{\tau}_j}{4} \right] \\
& + \frac{d G_\sigma^2}{2} \sum_{i \neq j \neq k} \delta^2(ijk) - \frac{d^2 G_\sigma^3}{2} \sum_{i \neq j \neq k \neq l} \delta^3(ijkl) \\
& + \frac{i}{4M^2} \sum_{i \neq j} A_{ij} \overleftarrow{\nabla}_i \delta(\vec{R}_{ij}) \times \overrightarrow{\nabla}_i . \vec{\sigma}_i ,
\end{aligned}
$$

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

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:**

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

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Derivation of effective Force (cont.)

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

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

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

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

Spin-orbit force predicted!

Note the totally new, subtle density dependence

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!

Important observation

- Simenel and McRae (ANU) noticed that the ratio of iso-vector to iso-scalar spin-orbit force in purely phenomenological UNDEF1 agrees with that predicted by QMC approach within 3%
- This may well be one part of the explanation of why it works so well for finite nuclei .... see next

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)

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

$$-17 < E/A < -15 \text{ MeV}$$

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

$$28 < S_0 < 34 \text{ MeV}$$

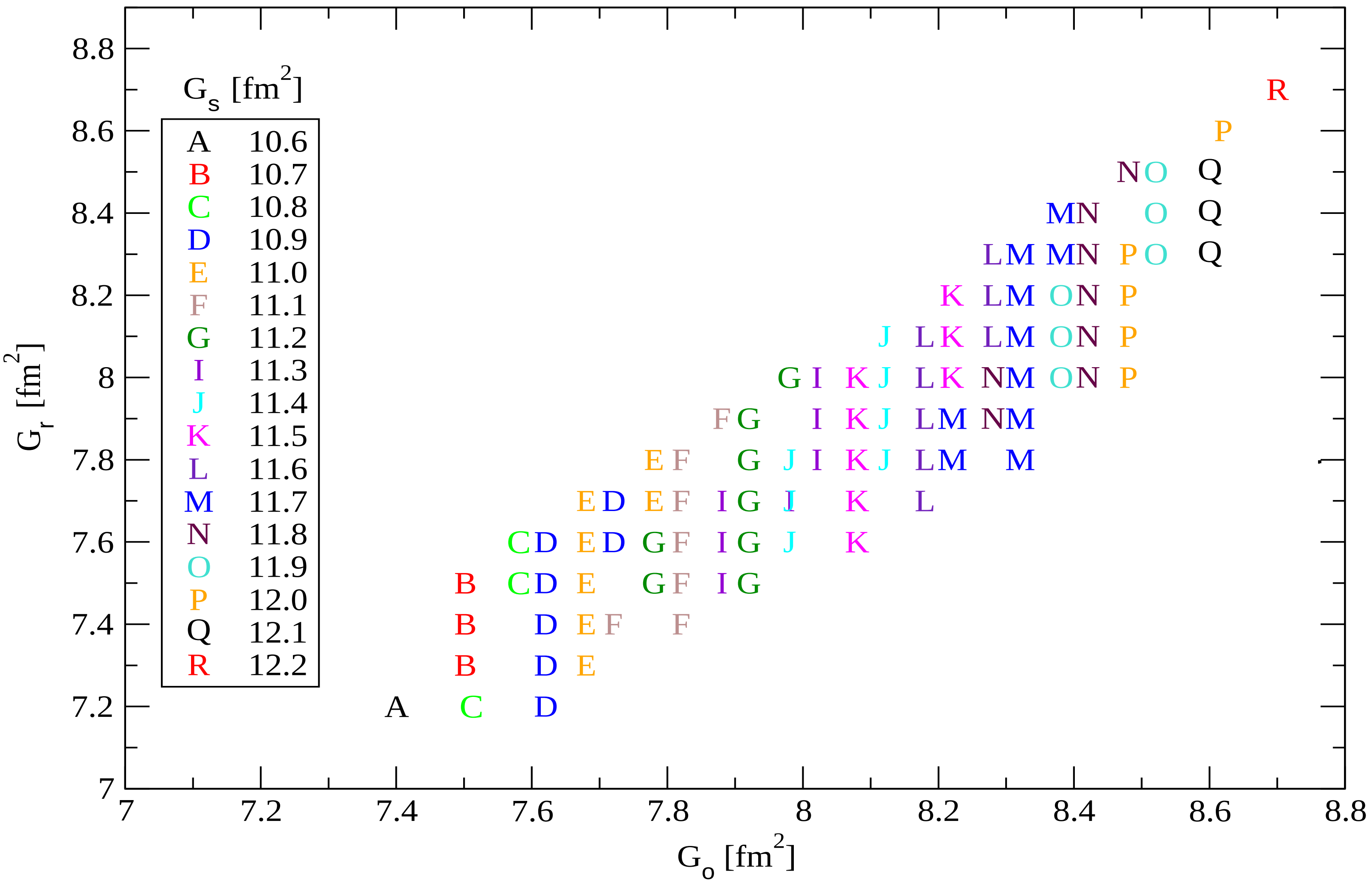
$$L > 20 \text{ MeV}$$

$$250 < K_0 < 350 \text{ MeV}$$

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

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

Overview of Allowed Parameters



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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			

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		

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i.e. Challenging cases of p- or n-rich nuclei across Periodic Table

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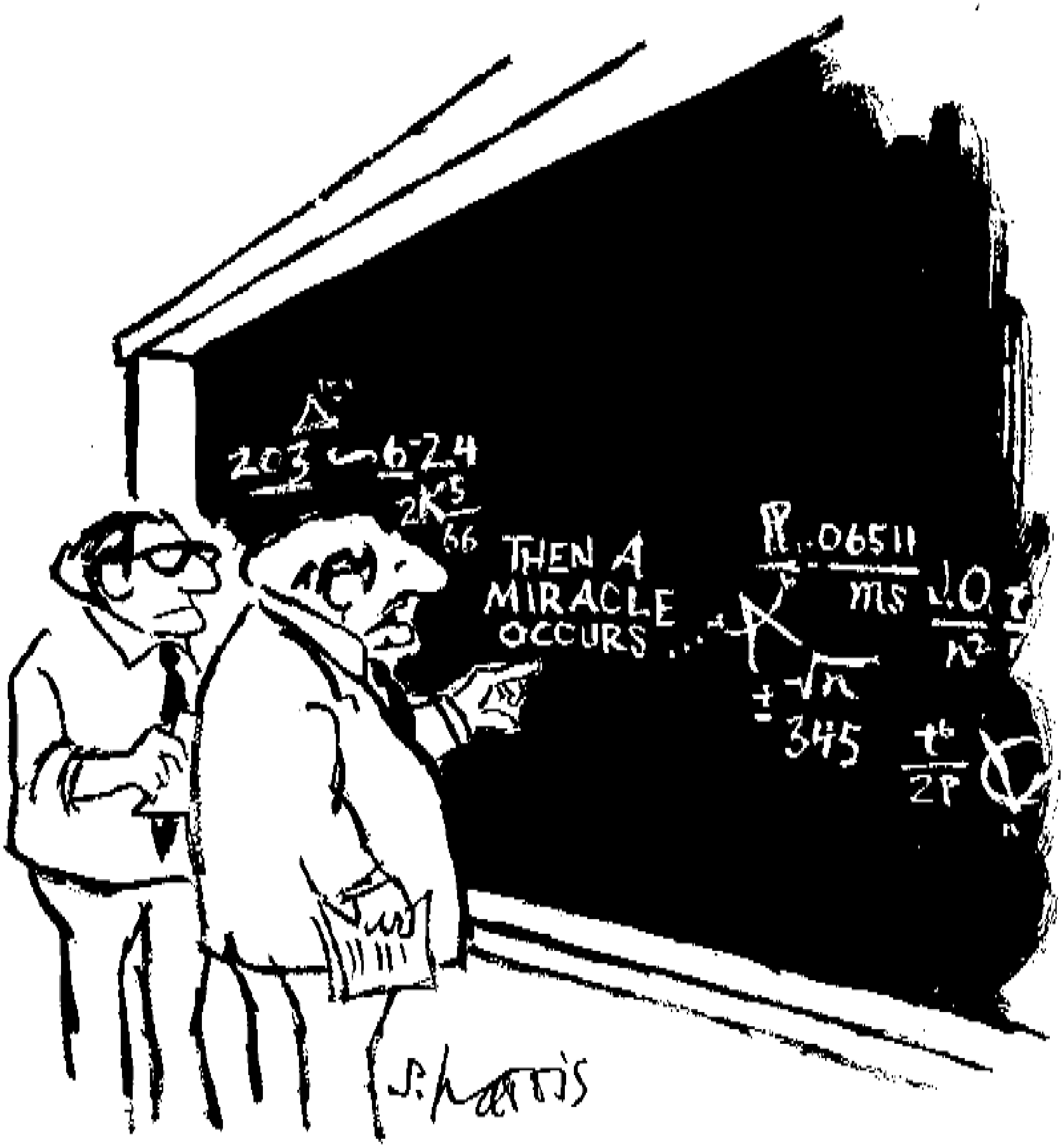

"I think you should be more explicit here in step two."

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

Not fit (superheavy nuclei, N=Z nuclei, mirror nuclei, other)

Stone et al., PRL (2016)

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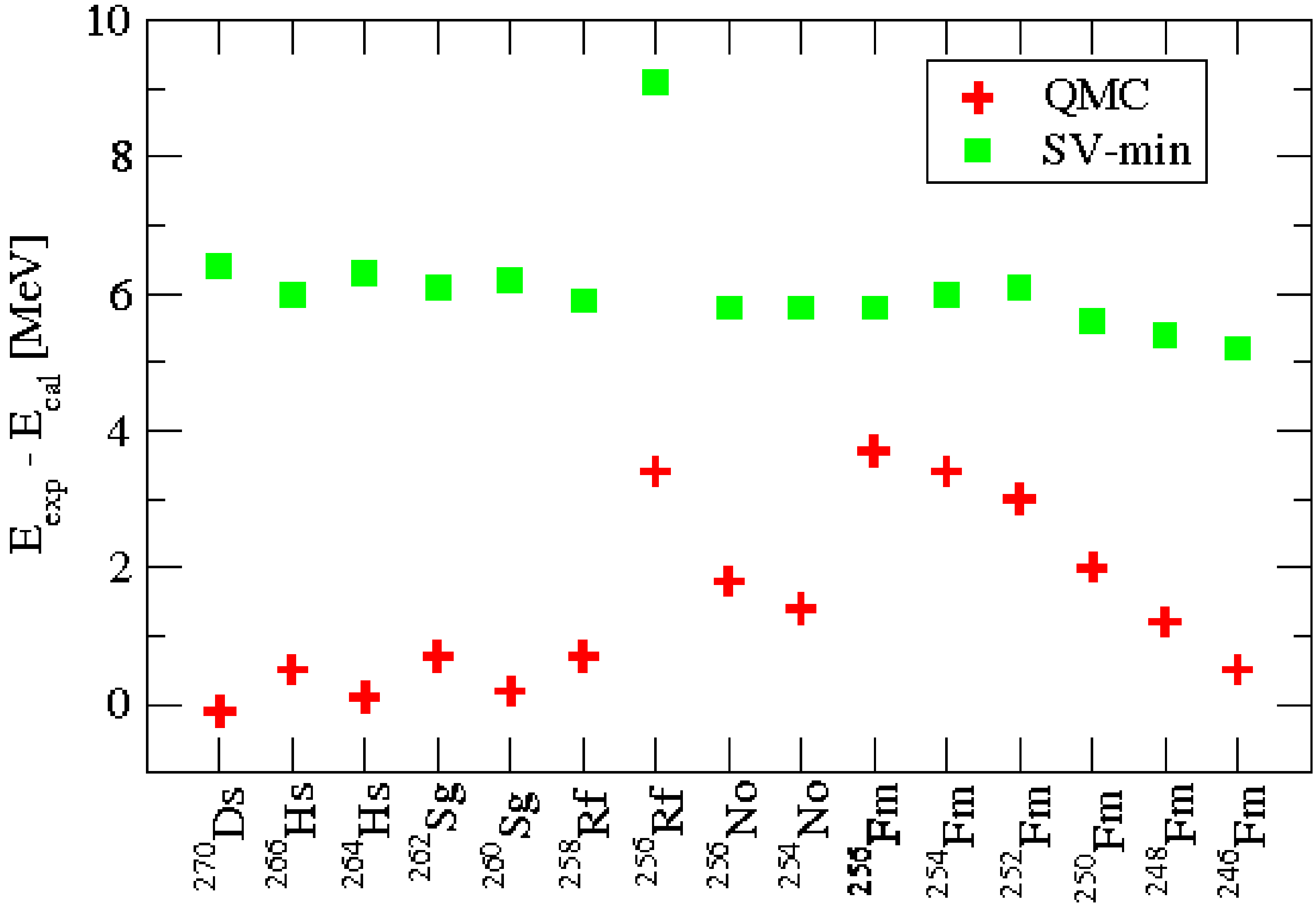
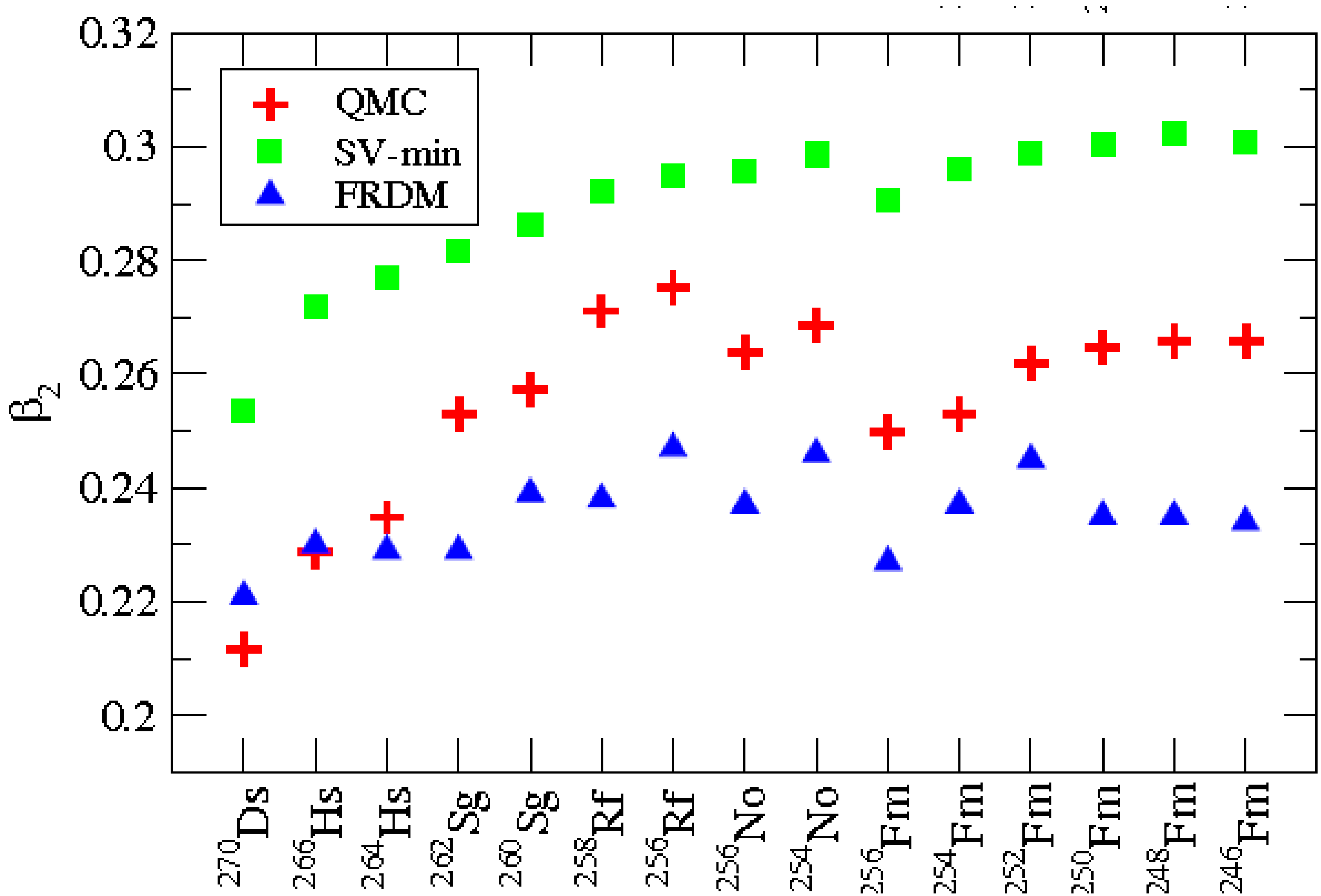
Superheavies : 0.1% accuracy



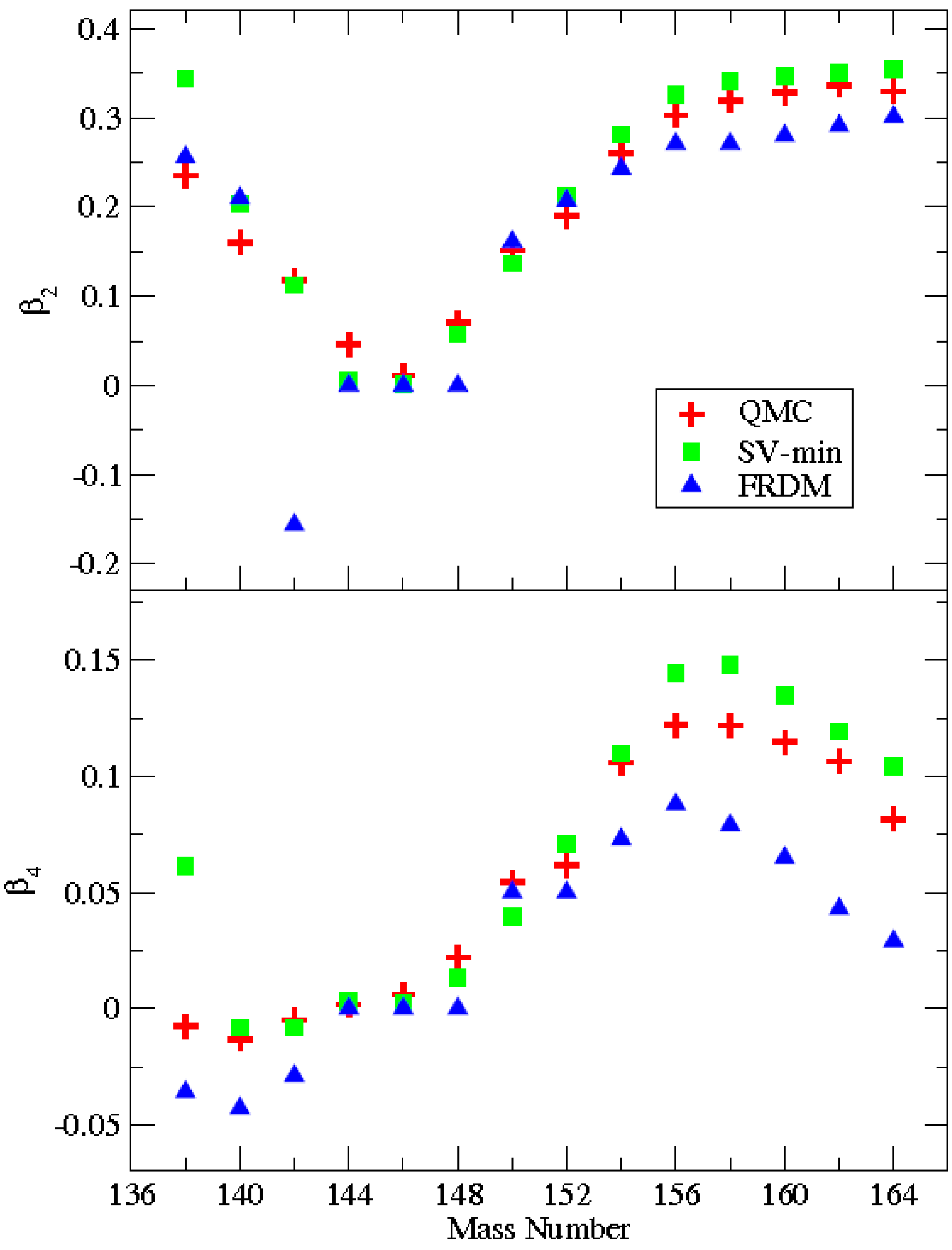
Stone et al., PRL (2016)

Quadrupole Deformation of Superheavies



Stone et al., PRL 116 (2016) 092501

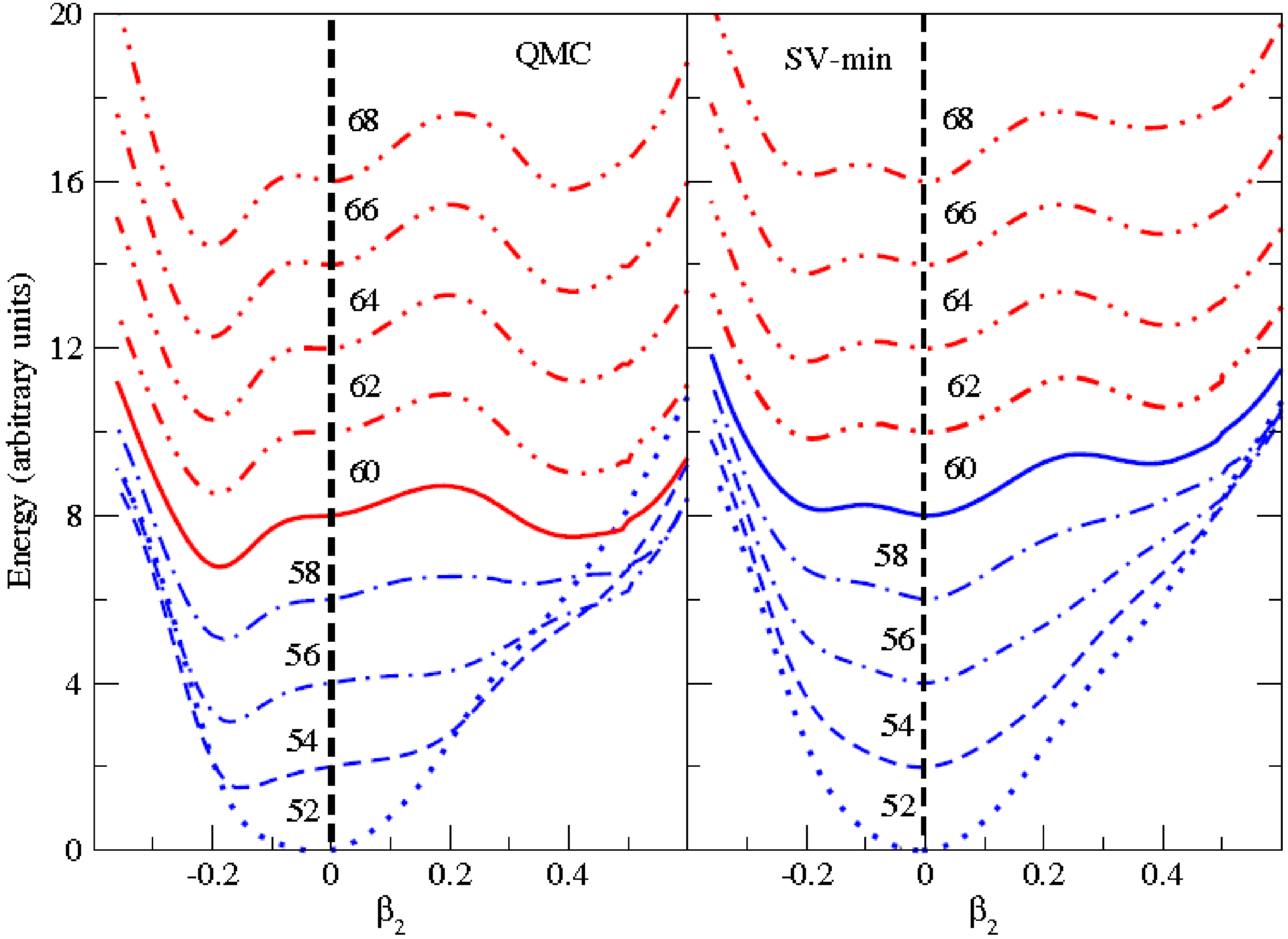
Deformation in Gd (Z=64) Isotopes



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

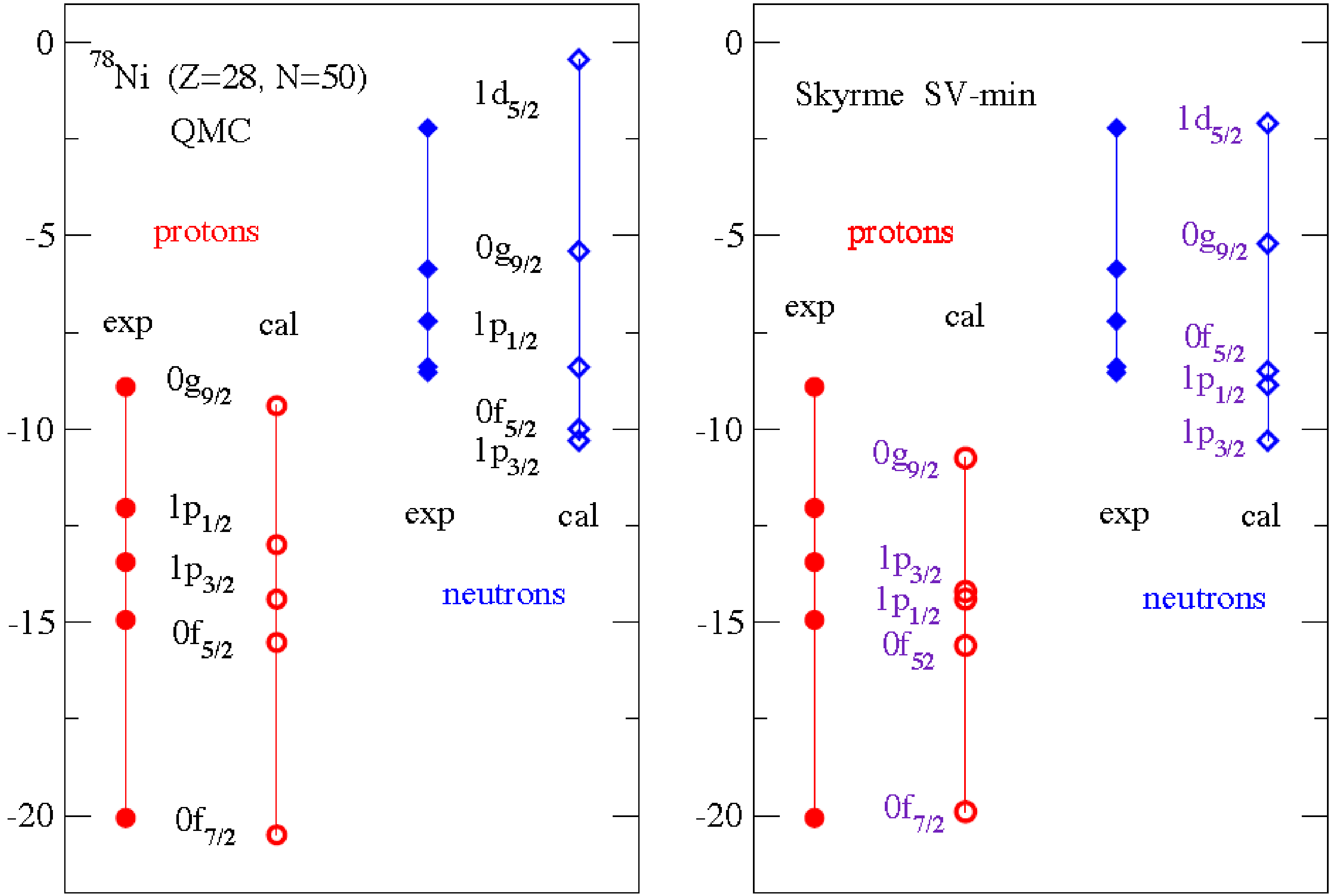


- **Shape co-existence sets in at N=60 – Sotty *et al*.,PRL115 (2015)172501**
- **Usually difficult to describe**

  – e.g. Mei et al., PRC85, 034321 (2012)

Stone et al., PRL 116 (2016) 092501

“Hot off the press”



Traditionally very hard to describe

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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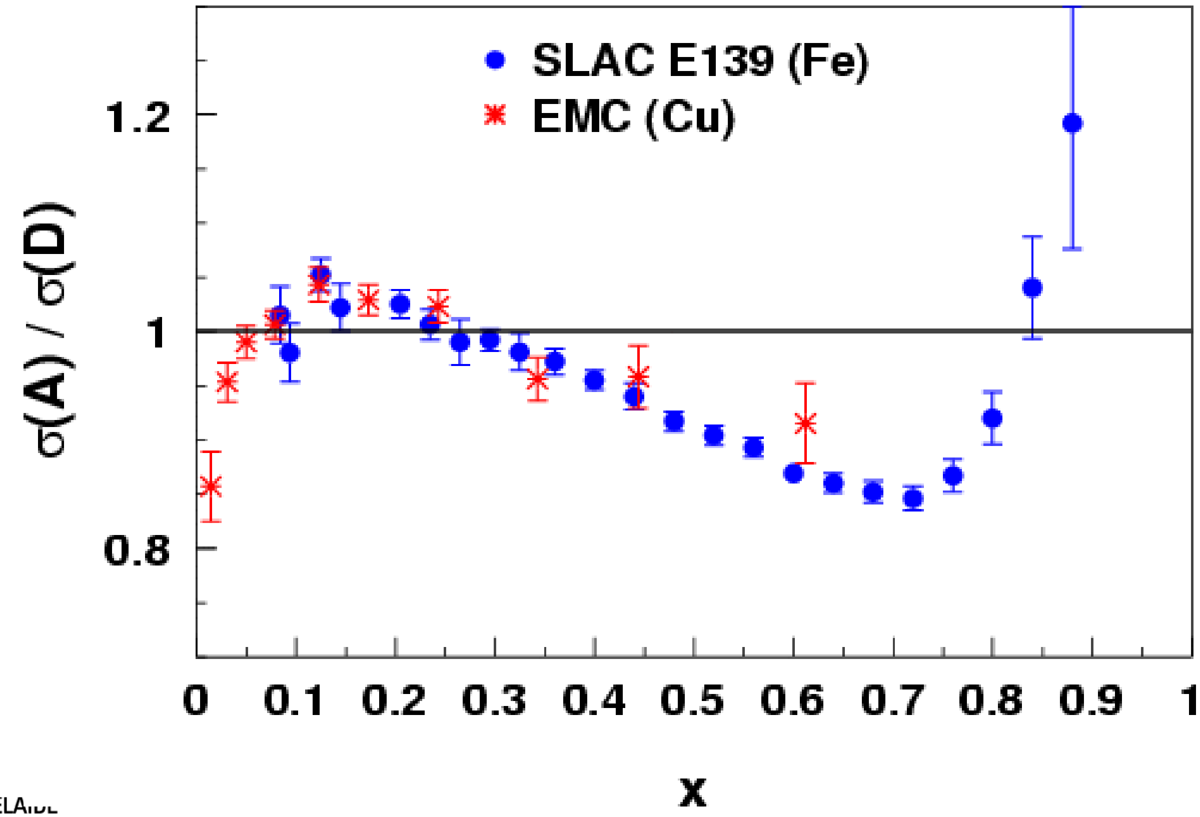
Nuclear DIS Structure Functions

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

Indeed, the approach described here is unique!

The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the HEP and Nuclear communities 30 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)

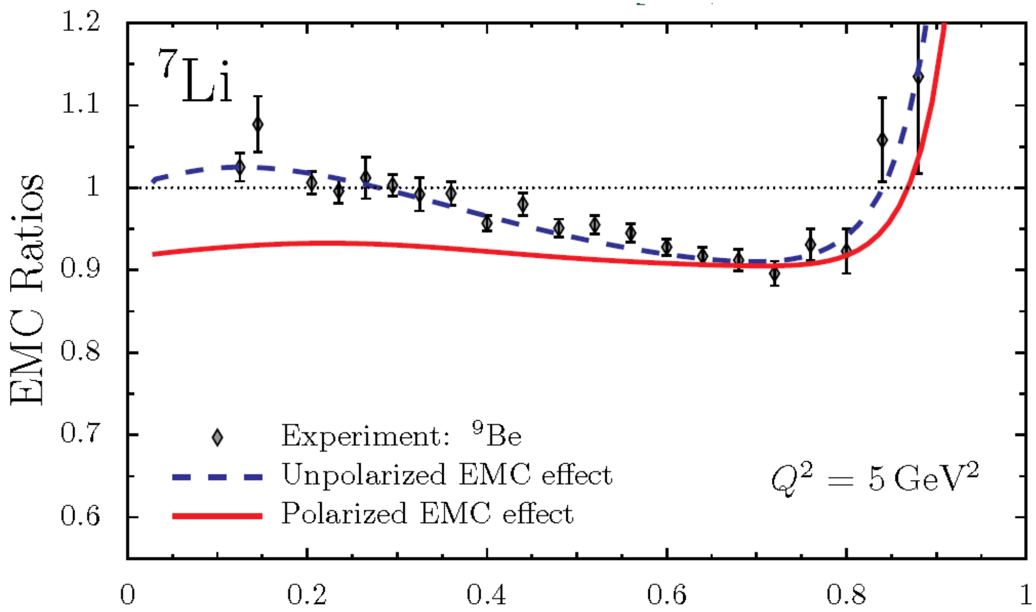
Theoretical Understanding

- **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 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

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*



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Other tests (e.g. Isovector EMC effect) – see Ian Cloet

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Modified Electromagnetic Form Factors In-Medium

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*

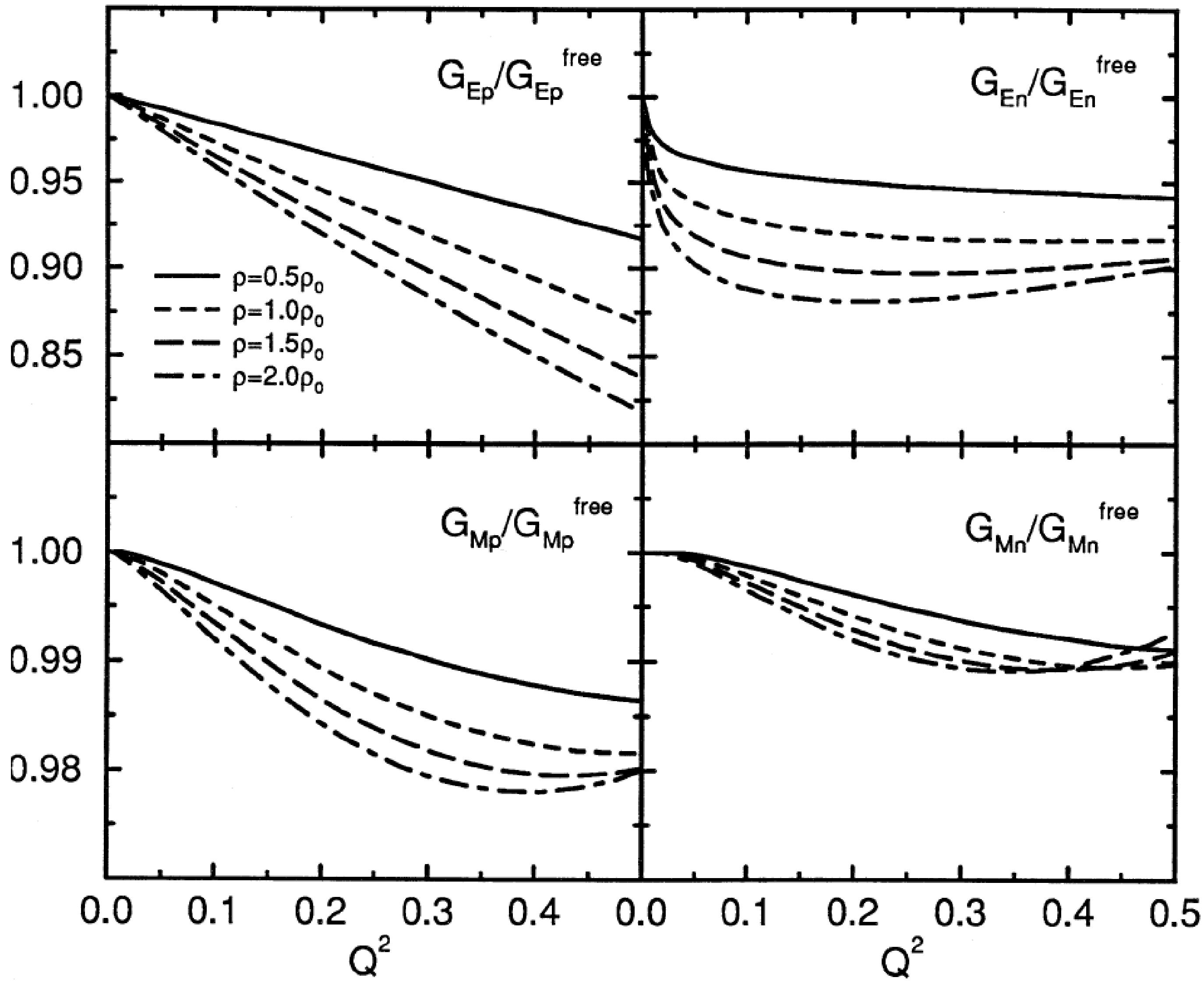
[b] *Physics Division, Tohoku College of Pharmacy, Sendai 981, Japan*

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.

In-medium electron-nucleon scattering

Archival

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

PHYSICAL REVIEW C, VOLUME 60, 068201

Electromagnetic form factors of the bound nucleon

D. H. Lu,[1,2] K. Tsushima,[2] A. W. Thomas,[2] A. G. Williams,[2] and K. Saito[3]
[1]*Department of Physics, National Taiwan University, Taipei 10617, Taiwan*
[2]*Department of Physics and Mathematical Physics and Special Research Centre for the Subatomic Structure of Matter, University of Adelaide, Adelaide, Australia 5005*
[3]*Physics Division, Tohoku College of Pharmacy, Sendai 981-8558, Japan*
(Received 24 July 1998; revised manuscript received 19 July 1999; published 5 November 1999)

We calculate electromagnetic form factors of the proton bound in specified orbits for several closed-shell nuclei. The shell structure of the finite nuclei, together with the internal quark substructure of the nucleon, are self-consistently described by the quark-meson-coupling model. We find that the medium-modified electric and magnetic form factors of the bound nucleon deviate considerably from those of the free nucleon. Our results suggest that this medium correction on the nucleon's quark substructure may be detectable in forthcoming quasielastic electron-nucleus scattering. [S0556-2813(99)00511-7]

Recent Calculations Motivated by:

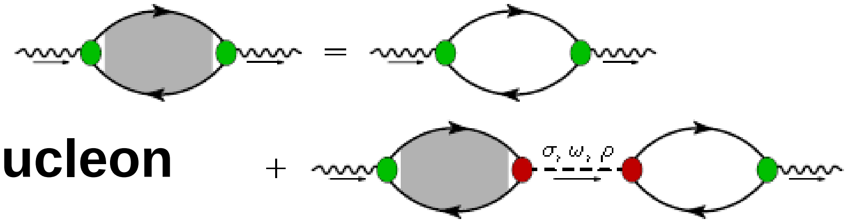
E01-015, PR-04-015 – Chen, Choi & Meziani

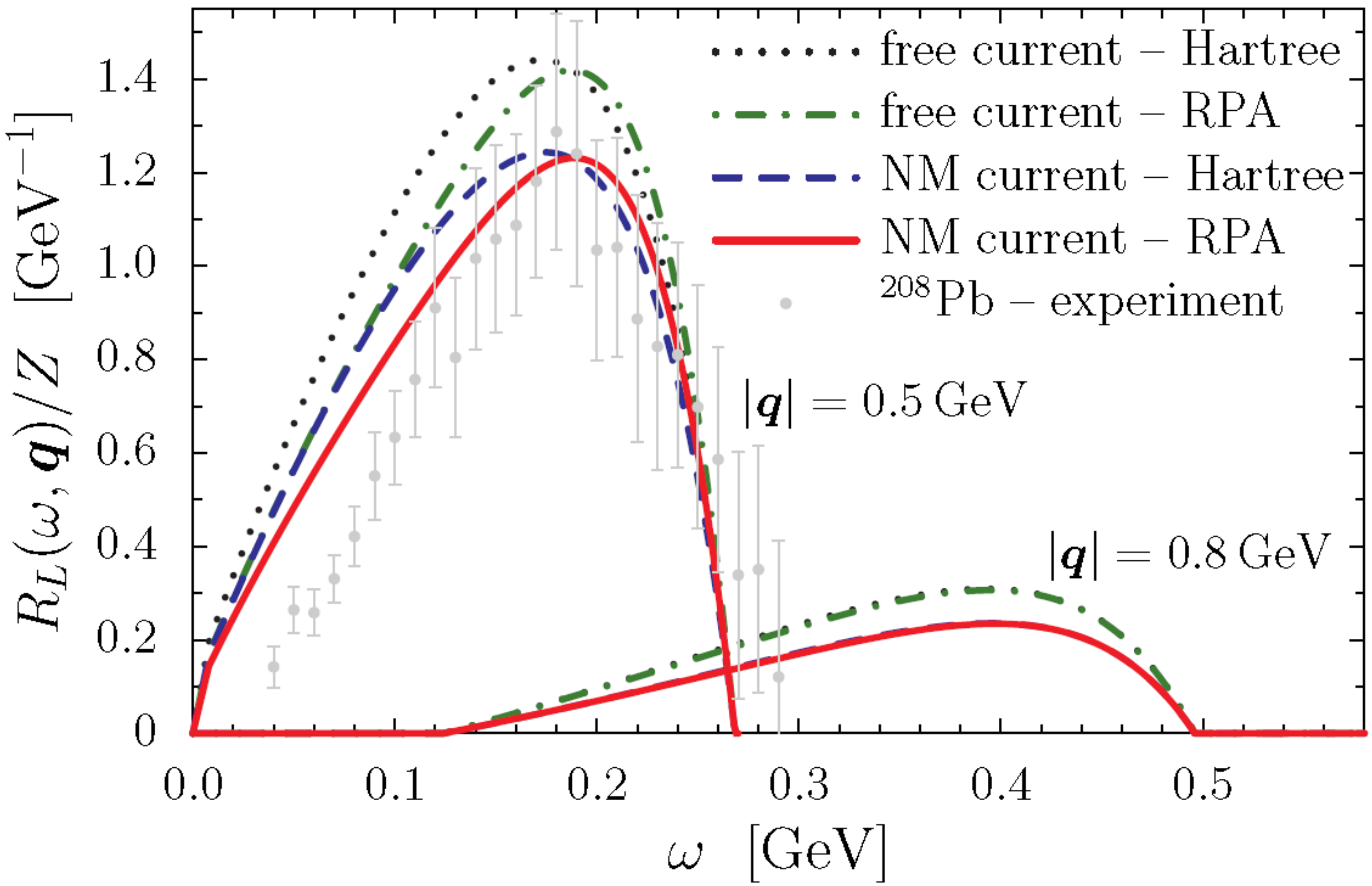
- Using NJL model with nucleon structure self-consistently solved in-medium
- Same model describing free nucleon form factors, structure functions and EMC effect

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





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

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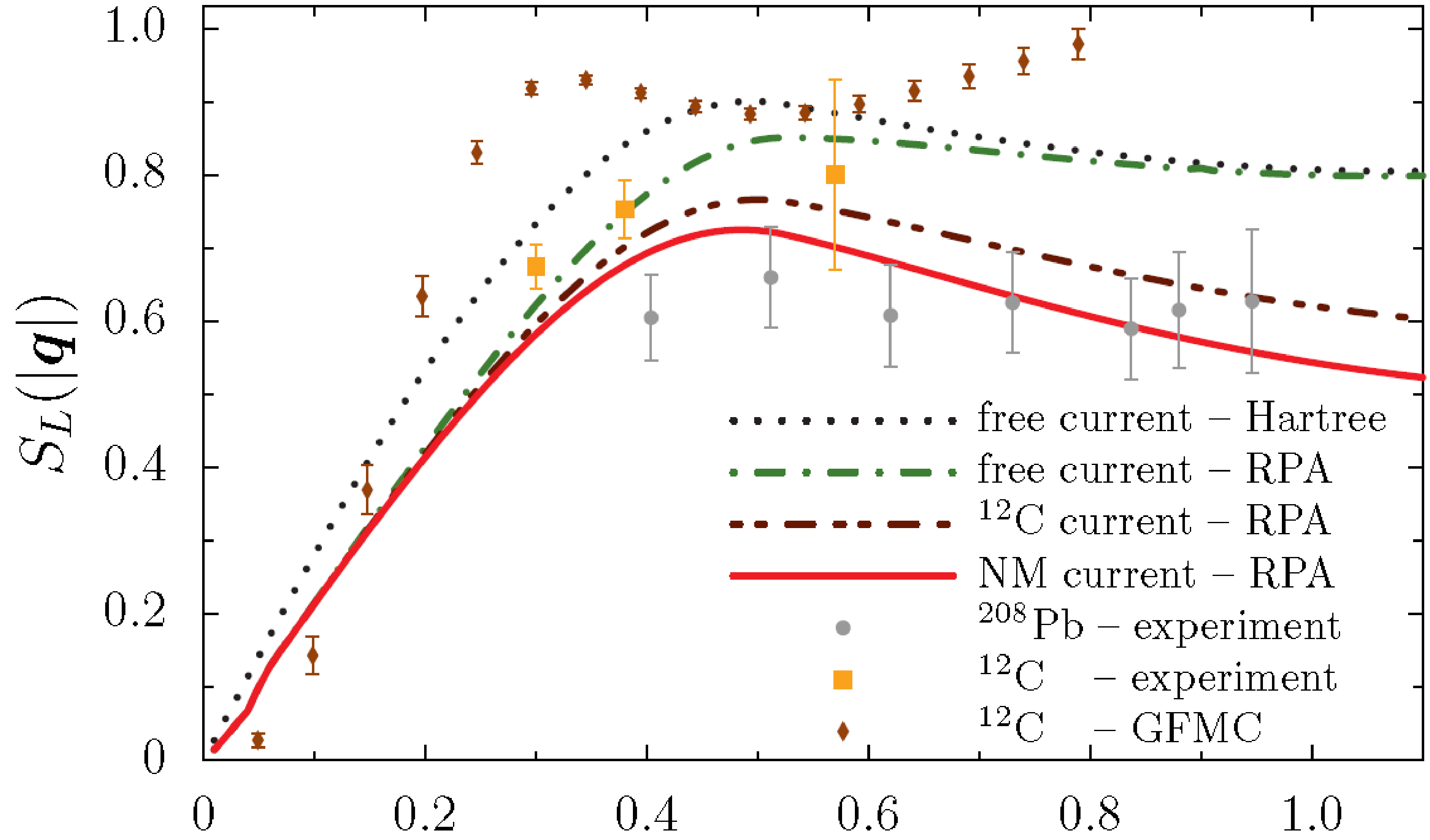
Comparison with Unmodified Nucleon & Data

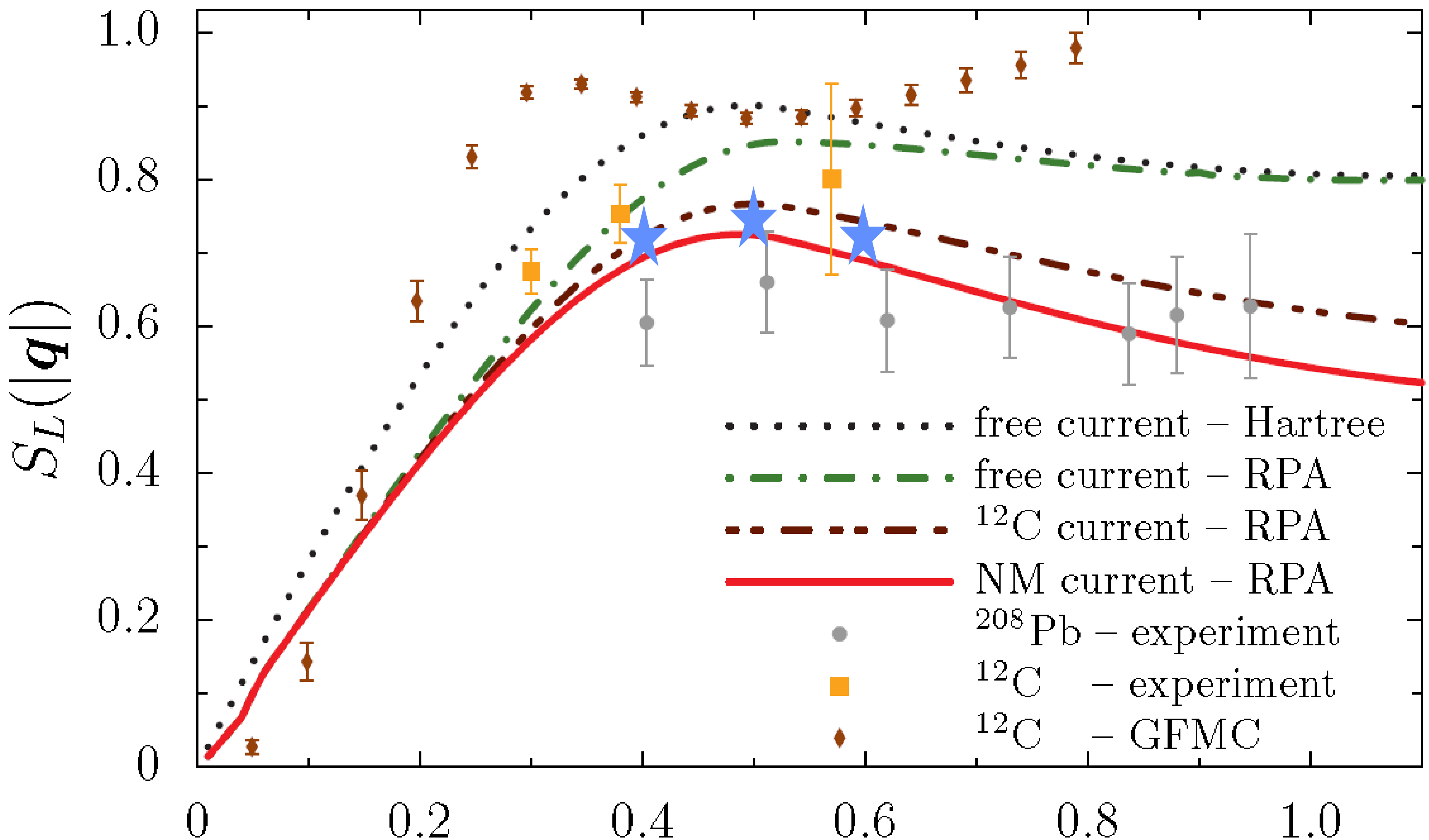


$$S_L(|\boldsymbol{q}|) = \int_{\omega+}^{|\boldsymbol{q}|} d\omega \, \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)}$$

Data: Morgenstern & Meziani

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

and these predictions are stable!



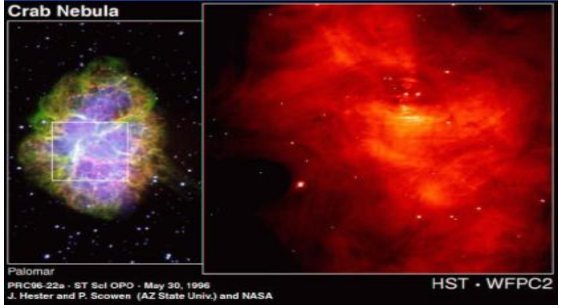
$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \, \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)}$$

★ Saito *et al.*, QMC 1999 (*op cit*)

Data: Morgenstern & Meziani

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

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......................**

We look forward to welcoming delegates to Adelaide, Australia for INPC 2016

September 11-16 2016

exceptional!

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Best Wishes Tony

FlamingText.com

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

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

- NO Σ hypernuclei are bound!

- Λ bound by about 30 MeV in nuclear matter (~Pb)

- Nothing known about Ξ hypernuclei – JPARC!

Λ- and Ξ-Hypernuclei in QMC

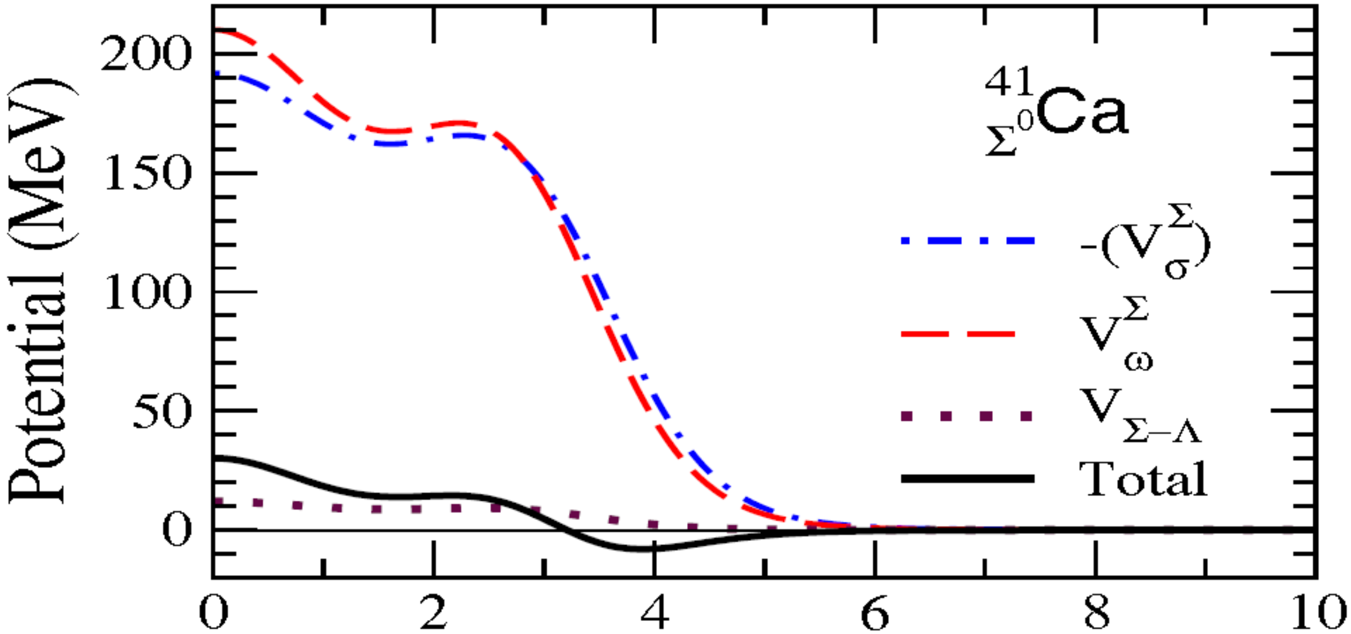
	${}^{89}_{\Lambda}$Yb (Expt.)	${}^{91}_{\Lambda}$Zr	${}^{91}_{\Xi^0}$Zr	${}^{208}_{\Lambda}$Pb (Expt.)	${}^{209}_{\Lambda}$Pb	${}^{209}_{\Xi^0}$Pb
$1s_{1/2}$	-22.5	-24.0	-9.9	-27.0	-26.9	-15.0
$1p_{3/2}$		-19.4	-7.0		-24.0	-12.6
$1p_{1/2}$	-16.0 ($1p$)	-19.4	-7.2	-22.0 ($1p$)	-24.0	-12.7
$1d_{5/2}$	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

Σ – hypernuclei

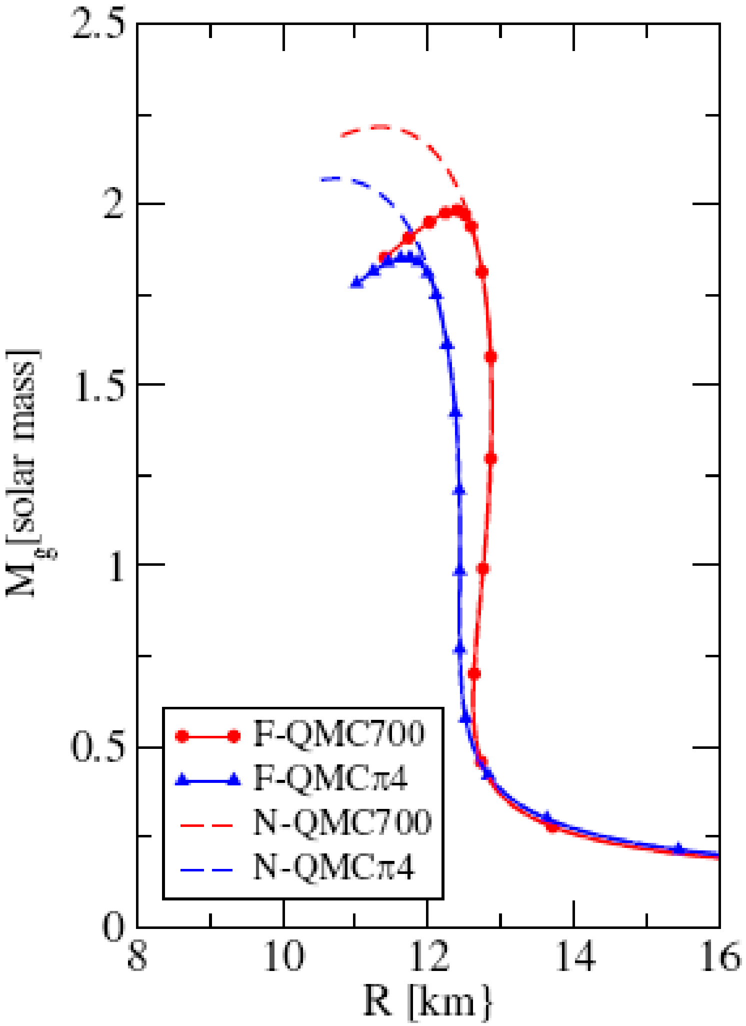
Σ-hypernuclei unbound :
because of increase of hyperfine interaction with density

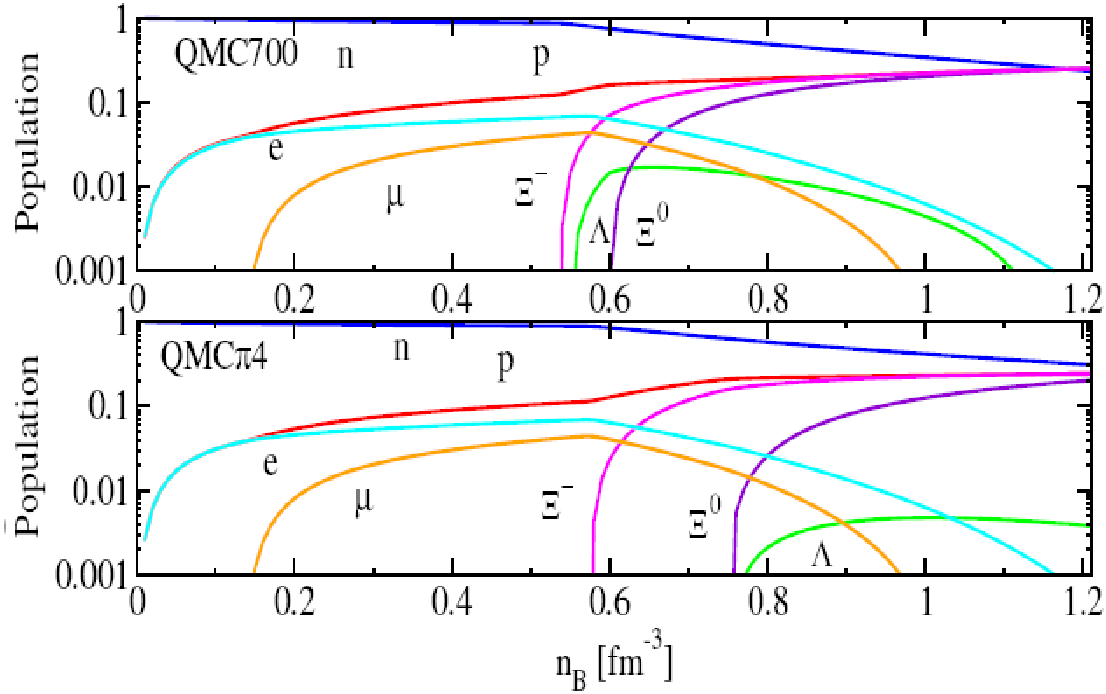
– e.g. for Σ^0 in ^{40}Ca:
central potential +30 MeV and few MeV attraction
in surface (-10MeV at 4fm)



Guichon *et al*., Nucl. Phys. A814 (2008) 66

Consequences for Neutron Star





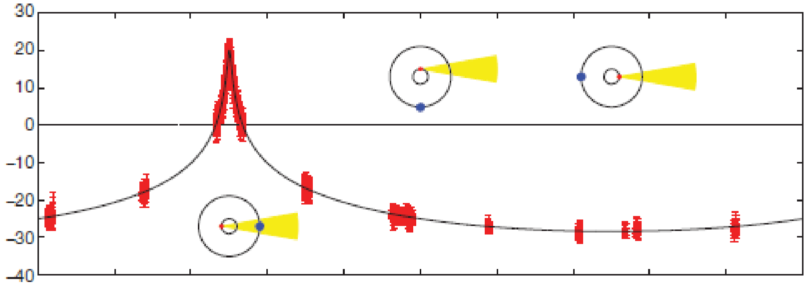
Rikovska-Stone et al., NP A792 (2007) 341

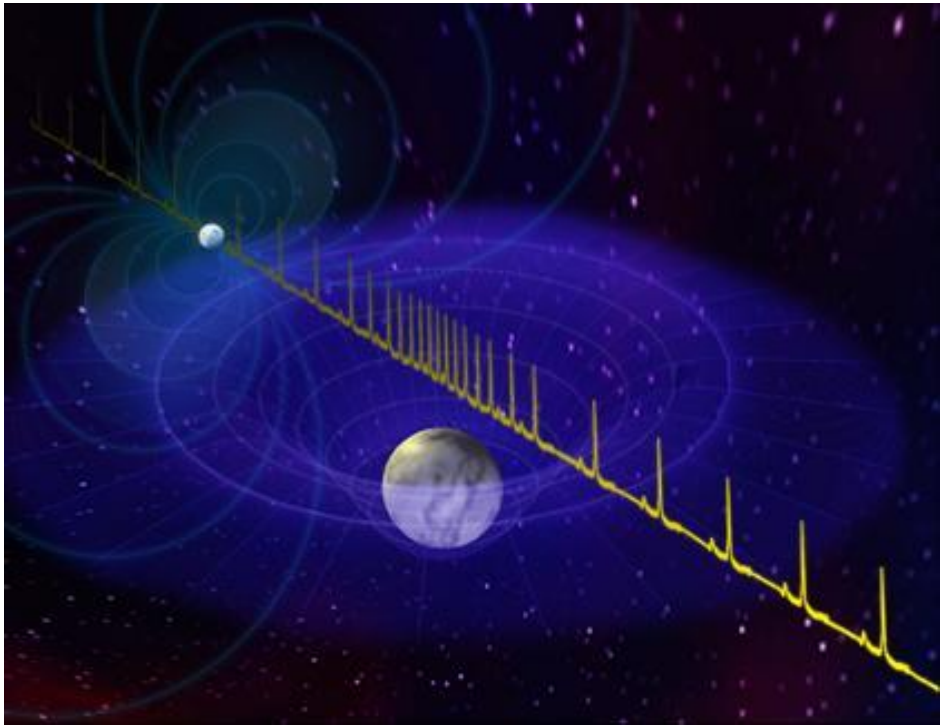
LETTER

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]





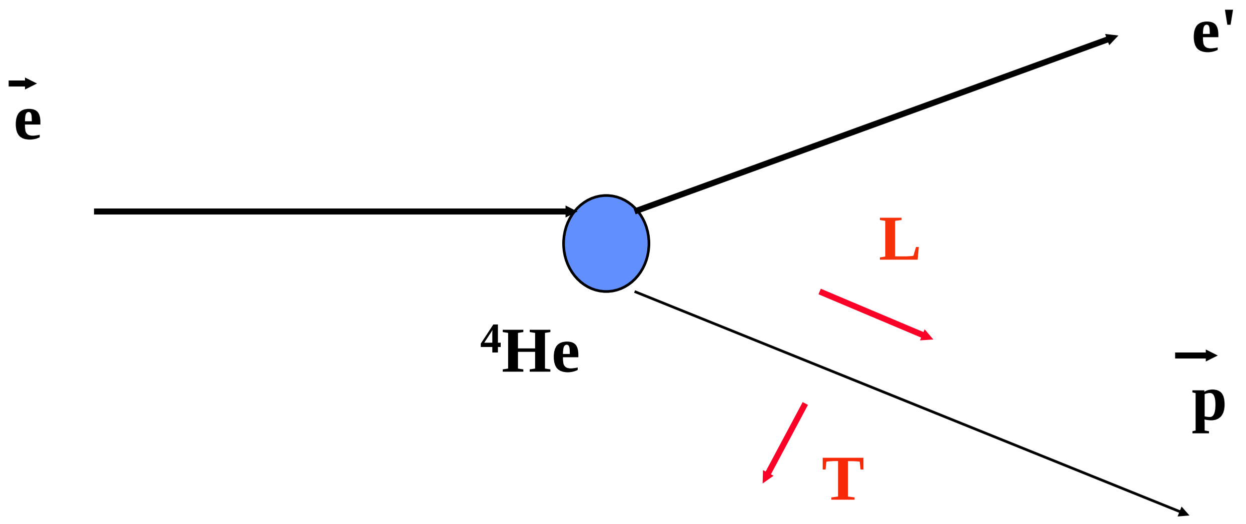
Report a very accurate pulsar mass much larger than seen before : 1.97 ± 0.04 solar mass

Claim it rules out hyperons (particles with strange quarks - ignored our *published* work!)

J1614-2230

Experimental Test of QMC at Mainz & JLab*

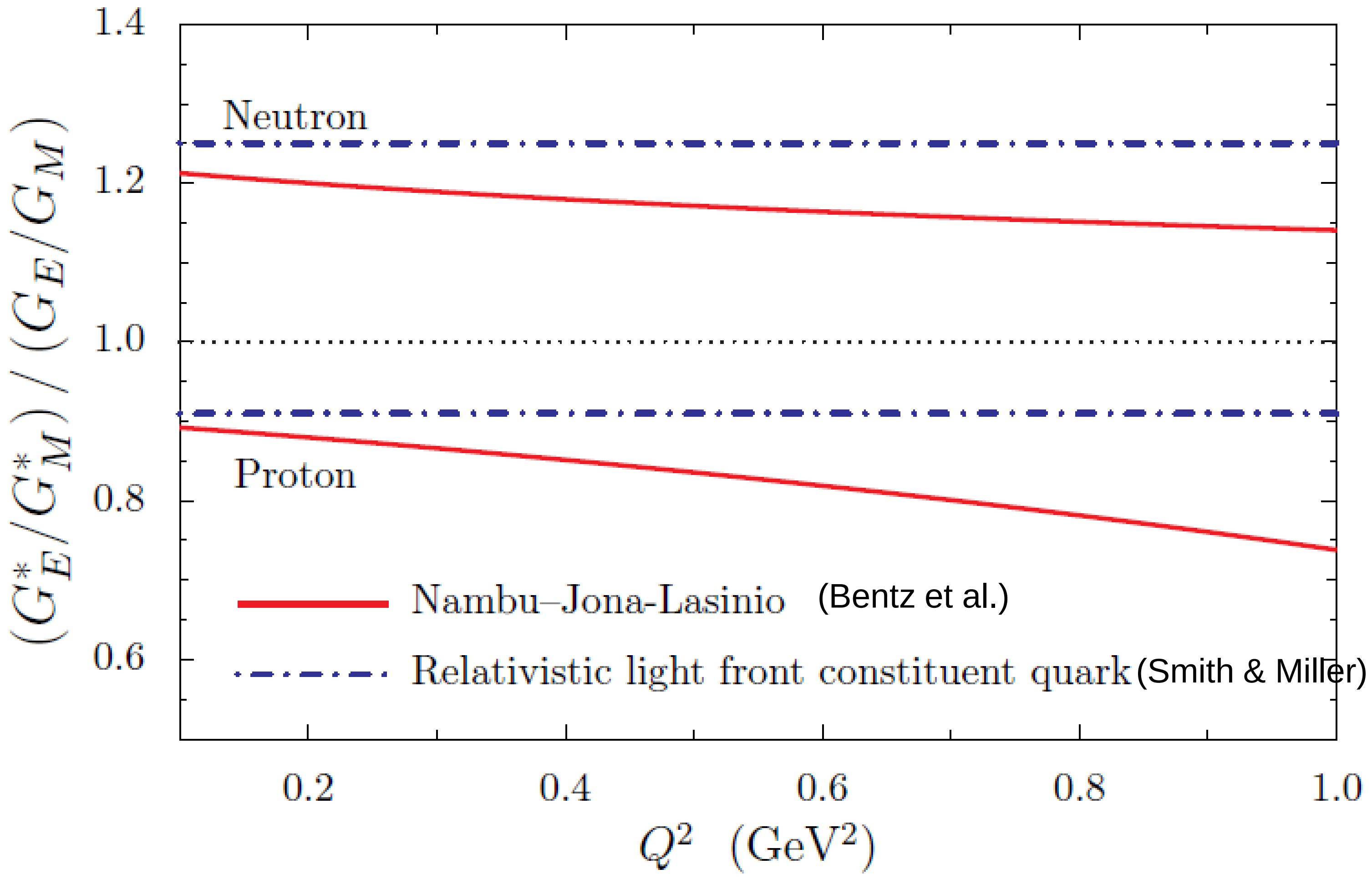
Capacity to measure polarization in coincidence:



$\sigma_T / \sigma_L \sim G_E/G_M$ **: Compare ratio in ^{4}He and in free space**

S. Dieterich *et al.* , Phys. Lett. B500 (2001) 47; and JLab report 2002

Super-ratio – in-medium to free space

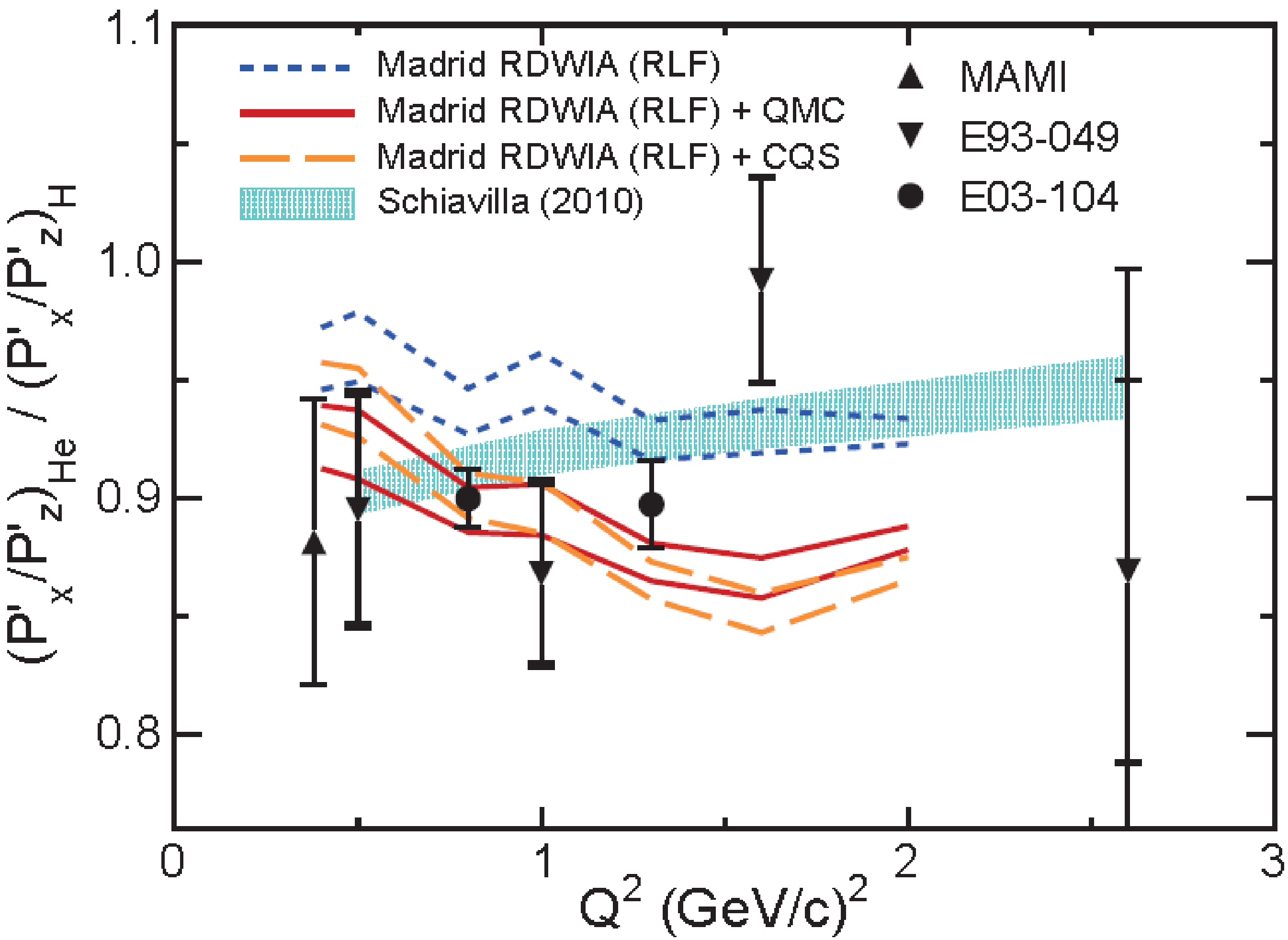


from - Cloet, Miller et al., arXiv:0903.1312

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)