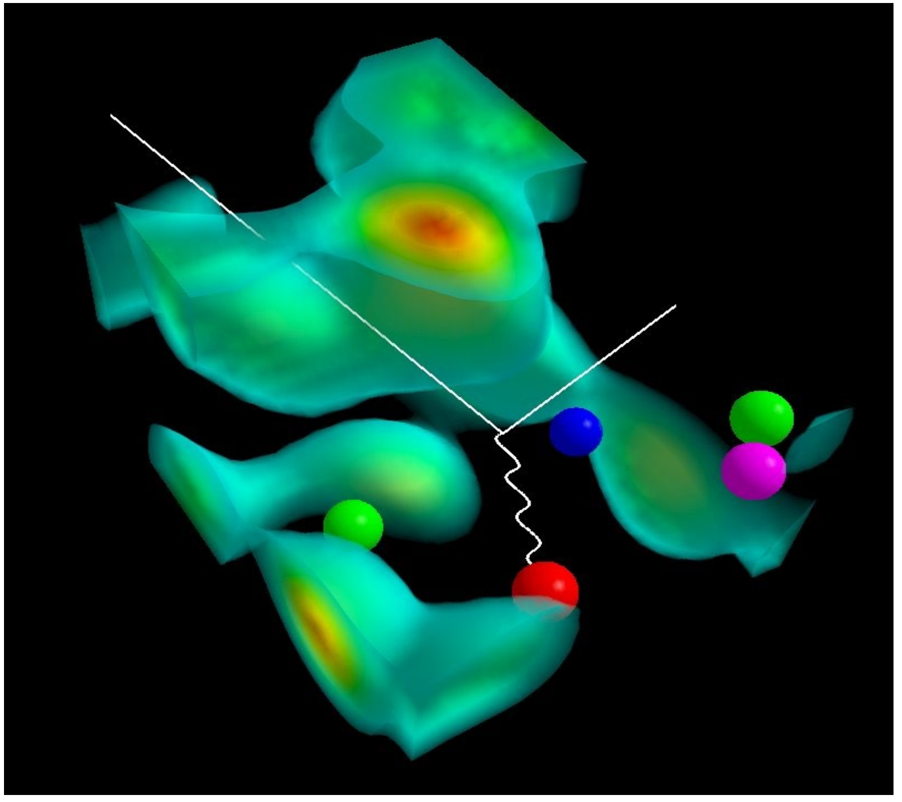
From the Quark and Gluon Structure of Nuclei to the Search for Dark Matter



Anthony W. Thomas

EIC Workshop – ICTP São Paulo
2nd May 2023

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DARK MATTER PARTICLE PHYSICS

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

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. New: Indication of a BSM particle: Dark Photon

I. Insights into nuclear structure

– what is the atomic nucleus?

There are two very different views….

Quark Structure matters/doesn't matter

- **Nuclear femtography: the science of mapping the quark and gluon structure of *atomic nuclei* is just beginning (EIC motivation)**

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

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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 not naturally described by EFT with N and π alone

Self-consistent solution for confined quarks in a hadron in nuclear matter

$$[i\gamma^\mu\partial_\mu - (m_q - g_\sigma{}^q\bar{\sigma}) - \gamma^0 g_\omega{}^q\bar{\omega}]\psi = 0$$

Source of σ changes: $\int_{Bag} d\vec{r}\,\bar{\psi}(\vec{r})\psi(\vec{r})$

SELF-CONSISTENCY

and hence mean scalar field changes…

and hence quark wave function changes….

THIS PROVIDES A NATURAL SATURATION MECHANISM (VERY <u>EFFICIENT BECAUSE QUARKS ARE LIGHT</u>)

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

Quark-Meson Coupling Model (QMC):
Role of the Scalar Polarizability of the Nucleon

The response of the nucleon internal structure to the scalar field is of great interest… and importance

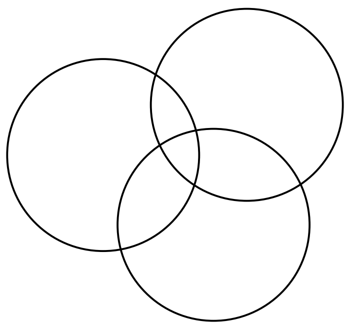
$$M^*(\vec{r}) = M - g_\sigma \sigma(\vec{r}) + \frac{d}{2}\left(g_\sigma \sigma(\vec{r})\right)^2$$

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

Indeed, in nuclear matter at mean-field level, this is the ONLY place the response of the internal structure of the nucleon enters.

Summary : Scalar Polarizability

- **Consequence of polarizability in atomic physics is many-body forces:**



$$V = V_{12} + V_{23} + V_{13} + V_{123}$$

  - **same is true in nuclear physics**

- **Three-body forces (NNN, HNN, HHN…) generated with NO new parameters**
  - **critical in neutron stars**

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:**

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

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Derivation of EDF (cont.)

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

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

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

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

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 ($g_\sigma{}^q$, $g_\omega{}^q$, $g_\rho{}^q$) so that nuclear matter properties are reproduced within errors

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

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

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

Overview of 106 Nuclei Studied – Across Periodic Table

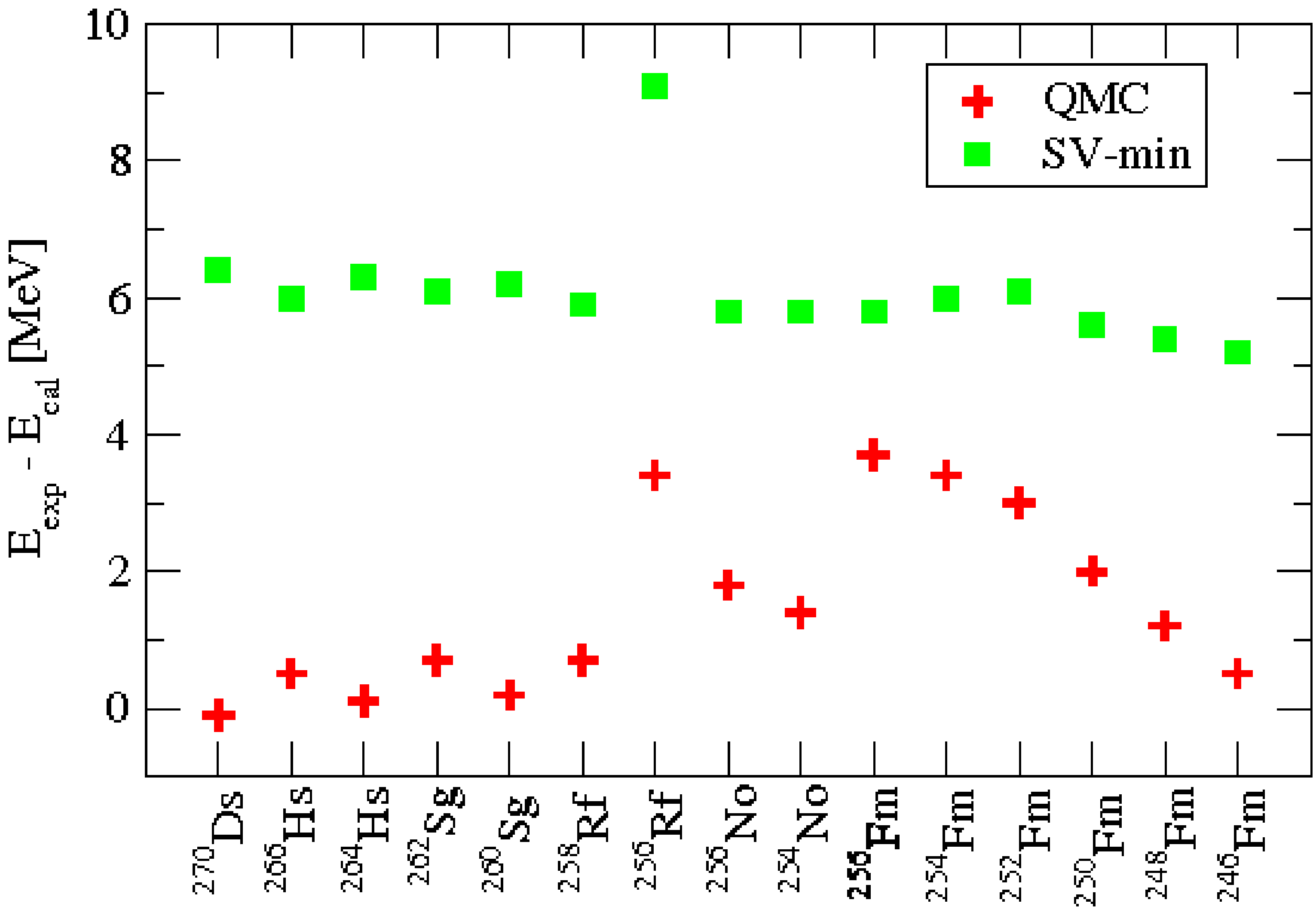
Element	Z	N	Element	Z	N
C	6	6 -16	Pb	82	116 - 132
O	8	4 -20	Pu	94	134 - 154
Ca	20	16 – 32	Fm	100	148 - 156
Ni	28	24 – 50	No	102	152 - 154
Sr	38	36 – 64	Rf	104	152 - 154
Zr	40	44 -64	Sg	106	154 - 156
Sn	50	50 – 86	Hs	108	156 - 158
Sm	62	74 – 98	Ds	110	160
Gd	64	74 -100			

Not fit

N	Z	N	Z
20	10 – 24	64	36 - 58
28	12 – 32	82	46 - 72
40	22 – 40	126	76 - 92
50	28 – 50		

i.e. We look at most challenging cases of p- or n-rich nuclei

Superheavy Binding : 0.1% accuracy



Stone et al., PRL 116 (2016) 092501

For detailed study of SHE see: arXiv:1901.06064

QMC π2

Includes better approximation to σ field, π Fock terms and term in σ^3

Giant Monopole Resonances

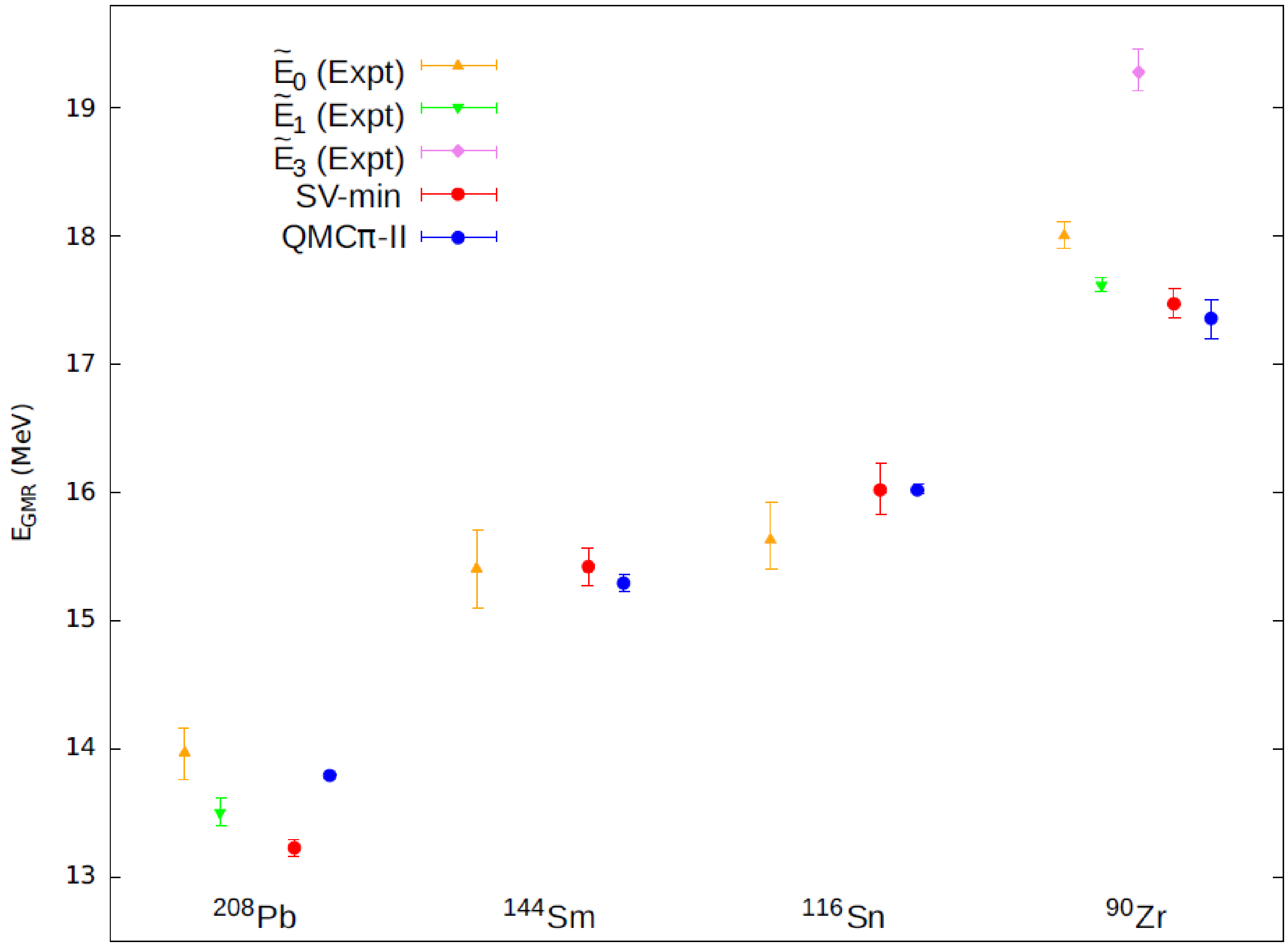


FIG. 13. GMR energies for ^{208}Pb, ^{144}Sm, ^{116}Sn, and ^{90}Zr from experiment and for the QMCπ-II and SVmin models. Experimental data are taken from Table 1 of Ref. [24].

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

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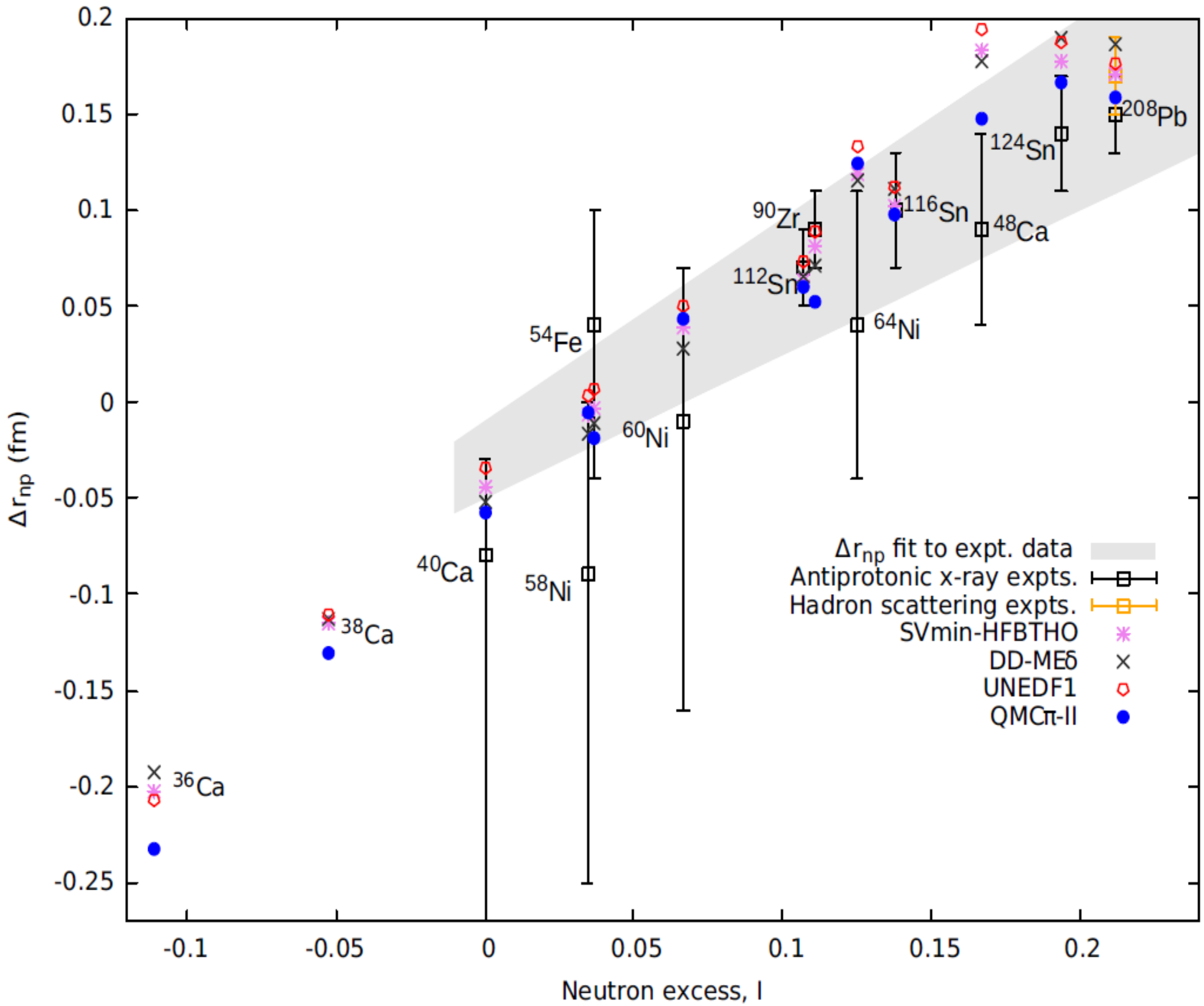
Neutron distributions



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

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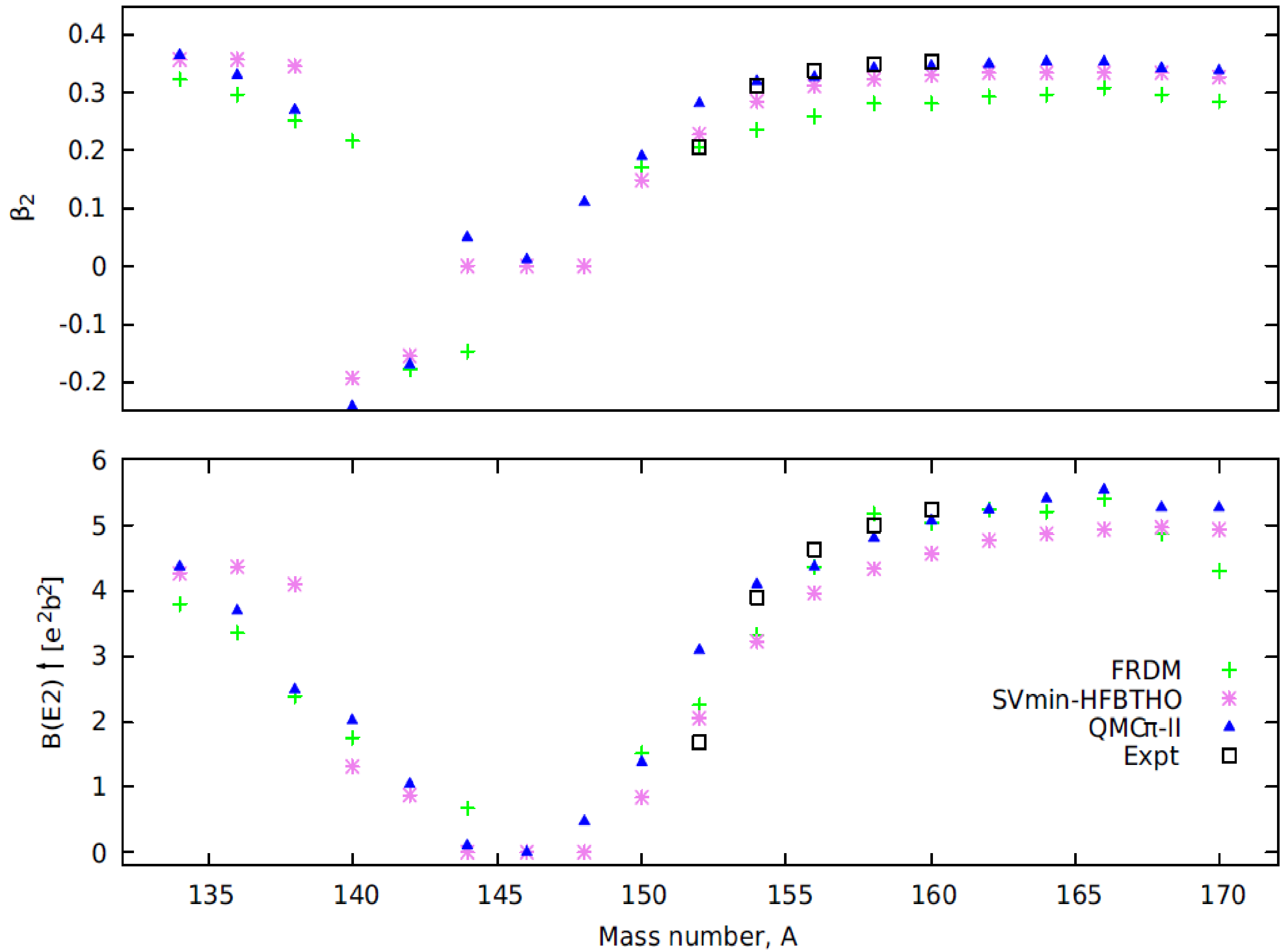
Deformation of Gd isotopes



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

More Nuclear Structure

All results for QMC-III from PhD thesis of Kay Martinez

- now at Silliman University (Philippines)
(publications in preparation)

QMC π3

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

$$H^J_{\sigma,\omega,\rho} = \left(\frac{G_\sigma(1-dv_0)^2}{4m_\sigma^2} - \frac{G_\omega}{4m_\omega^2}\right)\sum_m \vec{J}_m^2 - \frac{G_\rho}{4m_\rho^2}\sum_{m,m'} S_{m,m'}\vec{J}_m\cdot\vec{J}_{m'},$$

and

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

with

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

- Pairing interaction (simple BCS) derived in the model

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

$$d' = d + \tfrac{1}{3}G_\sigma\lambda_3.$$

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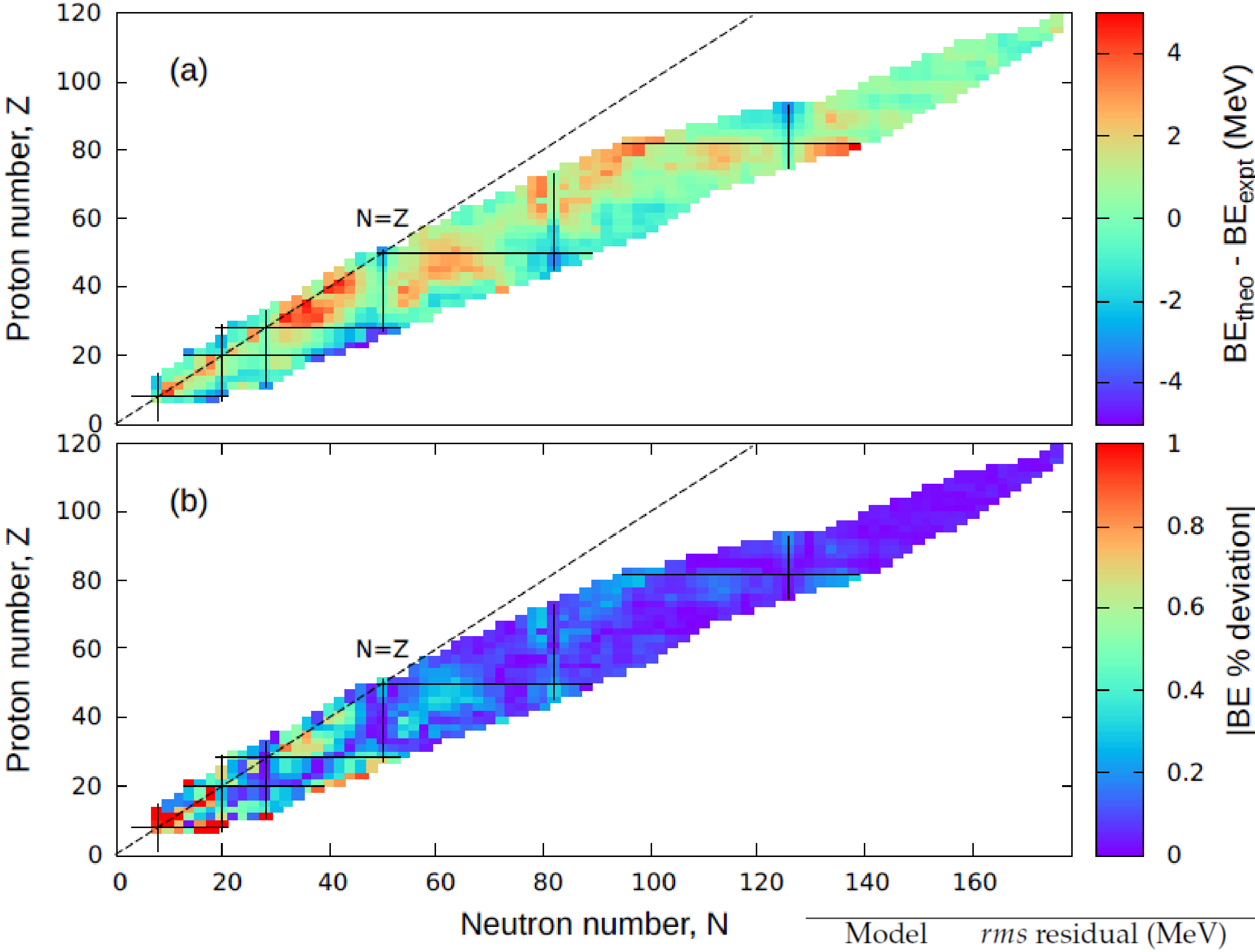
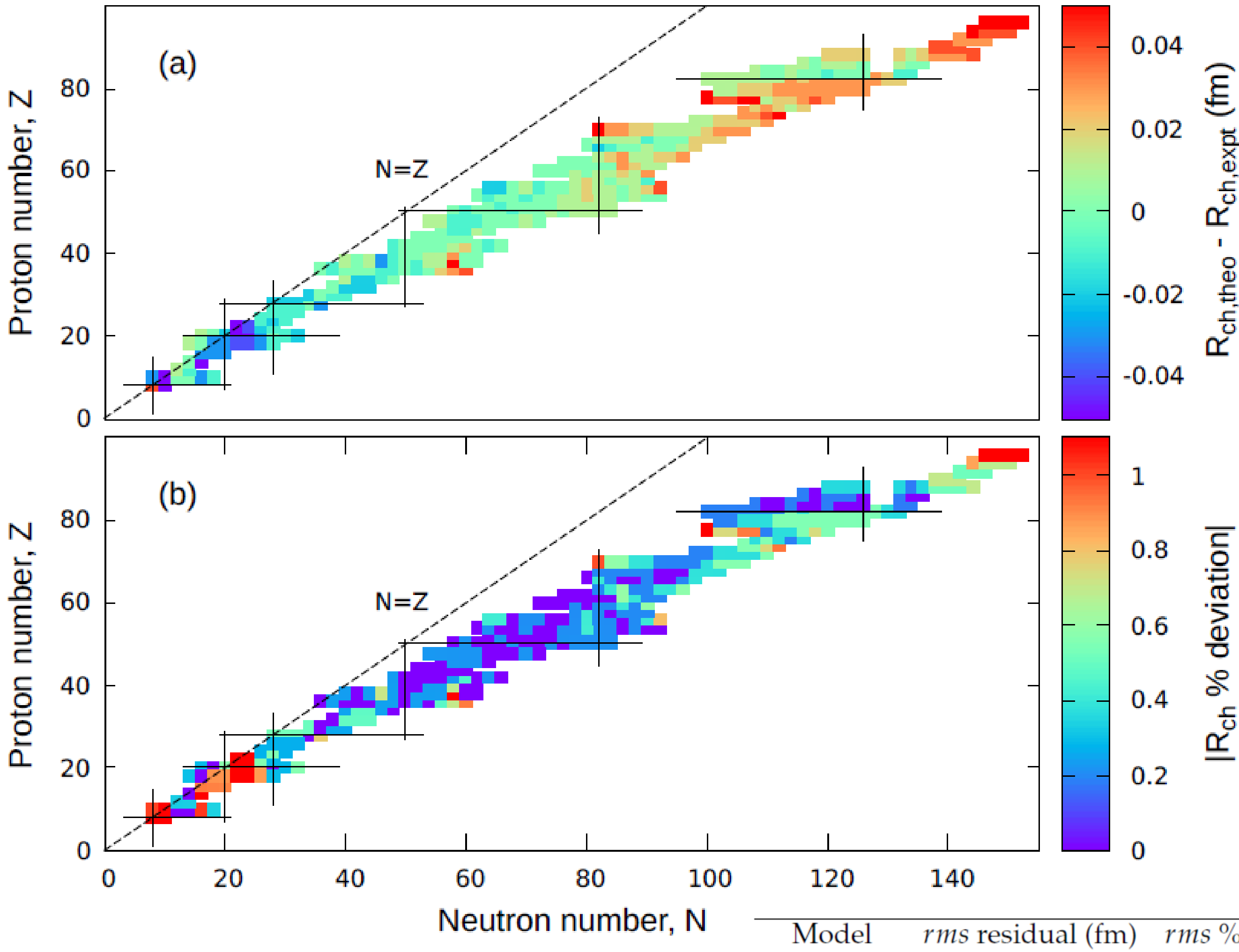
*cf. Over 20 in FRDM and typically 16 (11+5) in Skyrme forces

Binding Energies – All Known Even-Even Nuclei



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

Charge Radii



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

Separation energies: Drip Lines

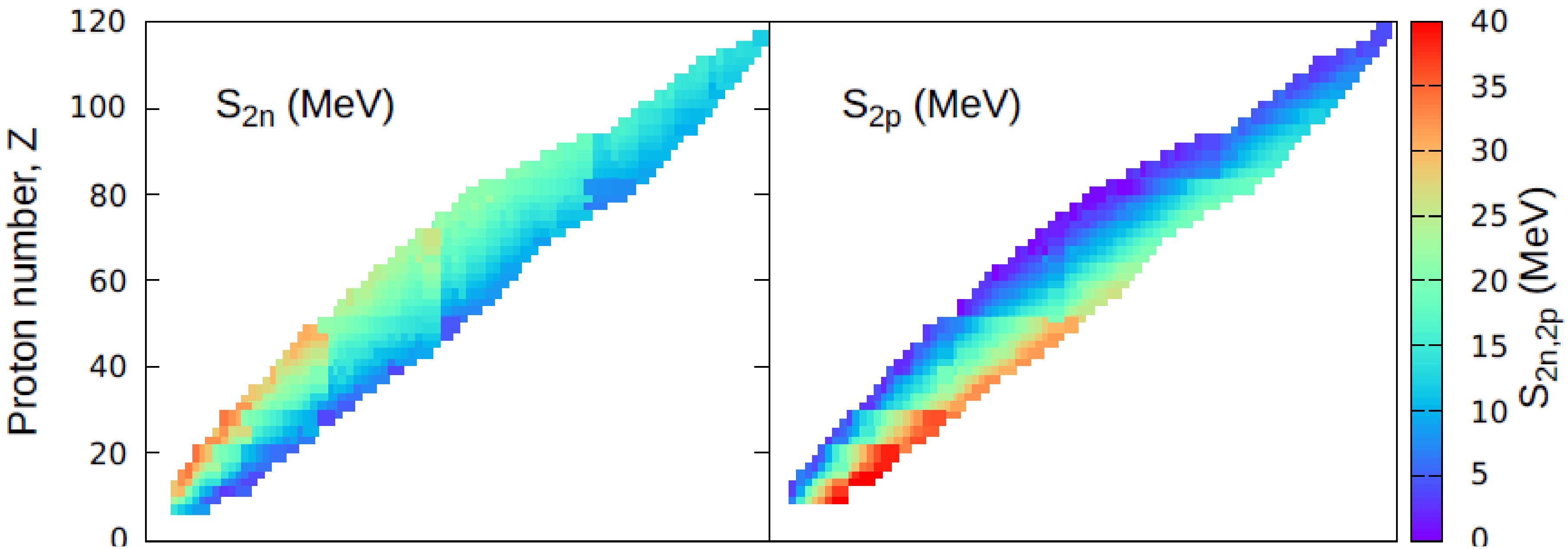


TABLE 7.3: Comparison of *rms* residuals for separation energies (in MeV) from QMC and from other nuclear models.

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

Deformation

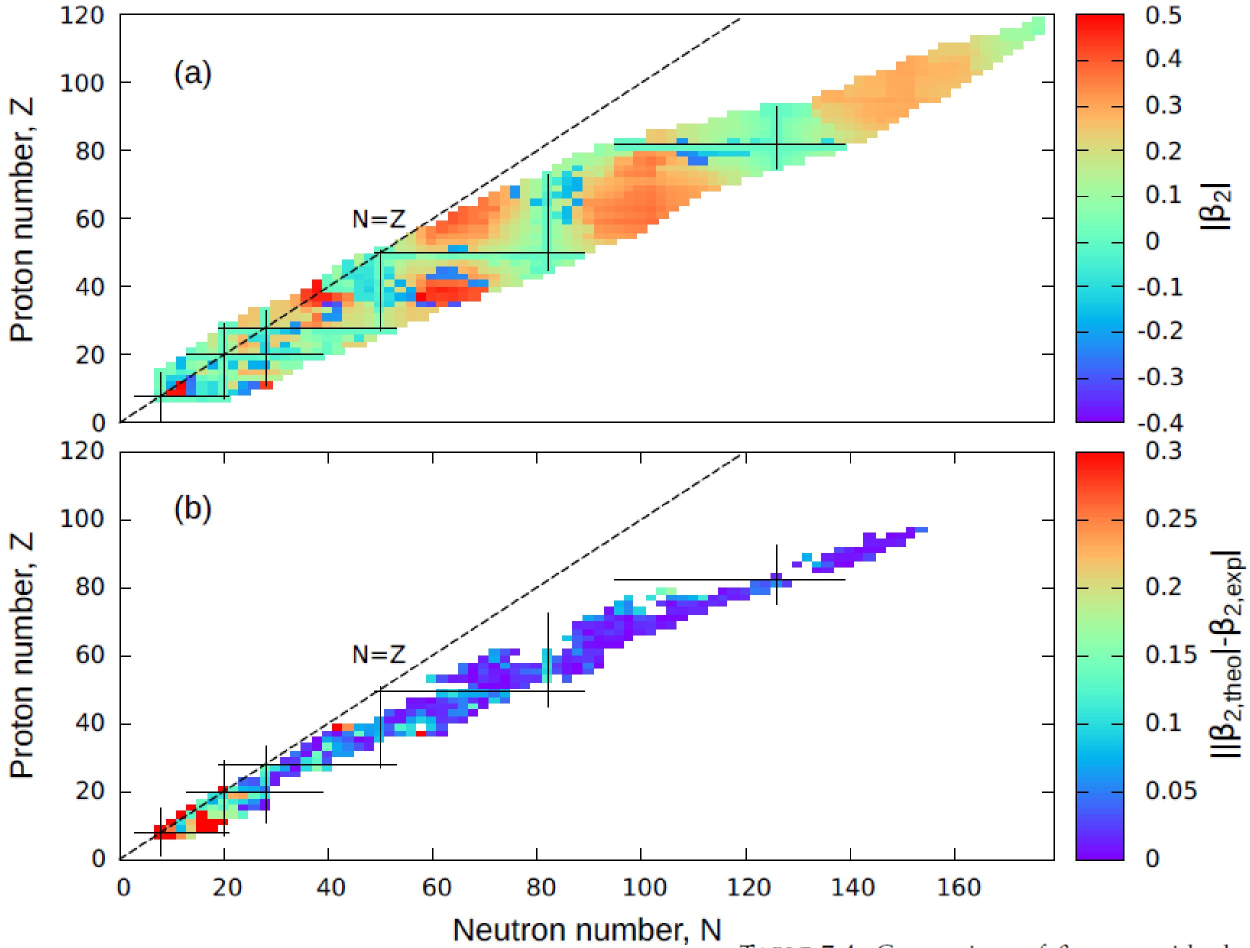
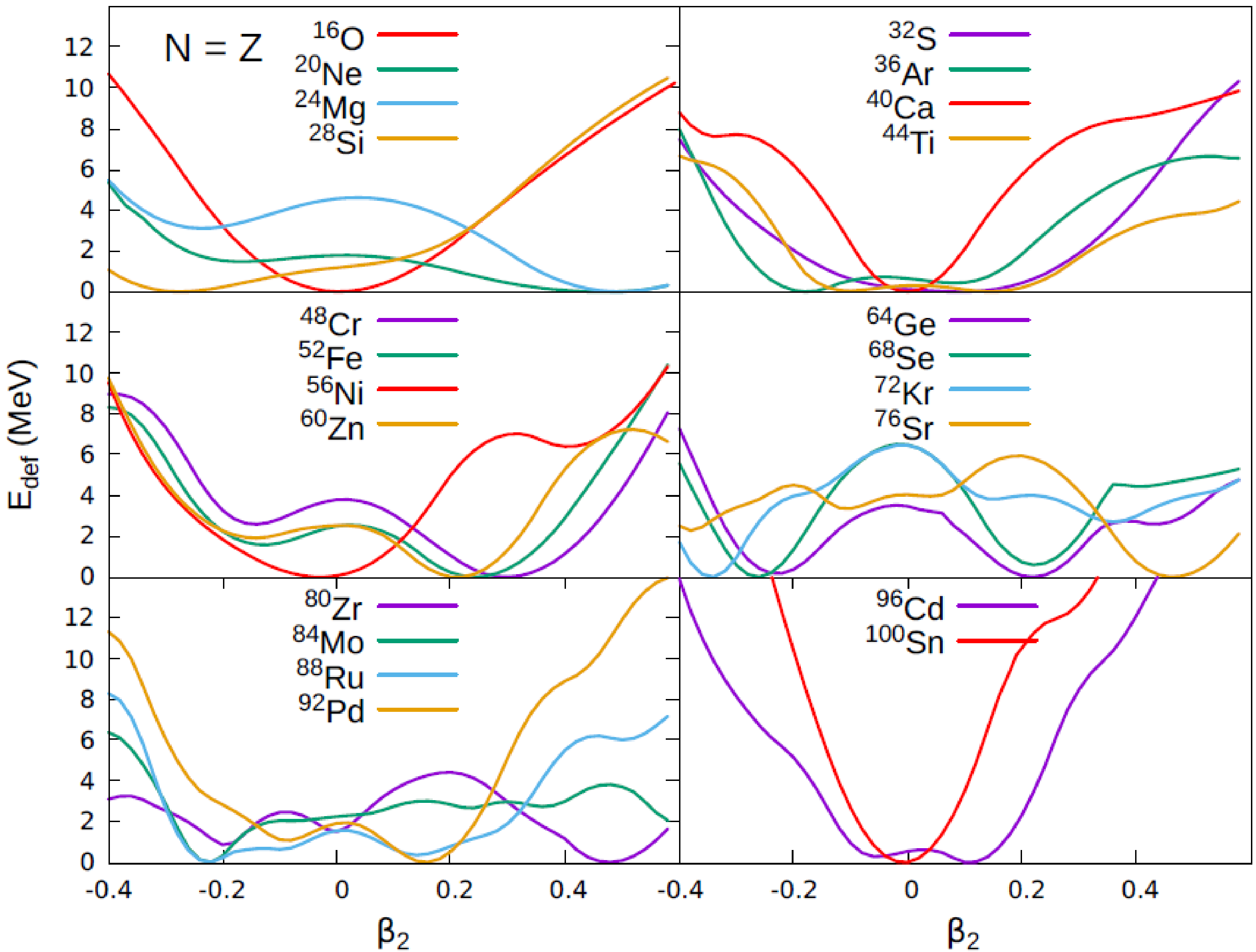


TABLE 7.4: Comparison of β_2 *rms* residuals and *rms* % deviations from QMCπ-III and from other nuclear models. There are a total of 324 even-even nuclei with available data for β_2 included for comparison.

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

Shape Co-Existence for Z=N



The Superheavy Region

First study:

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

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

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and Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA

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Department of Physics, Kyushu University, Nishi-ku, Fukuoka 819-0395, Japan
and RIKEN Nishina Center, RIKEN, Wako-shi, Saitama 351-0198, Japan

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

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

Updated and expanded here (Martinez thesis)

Binding Energies

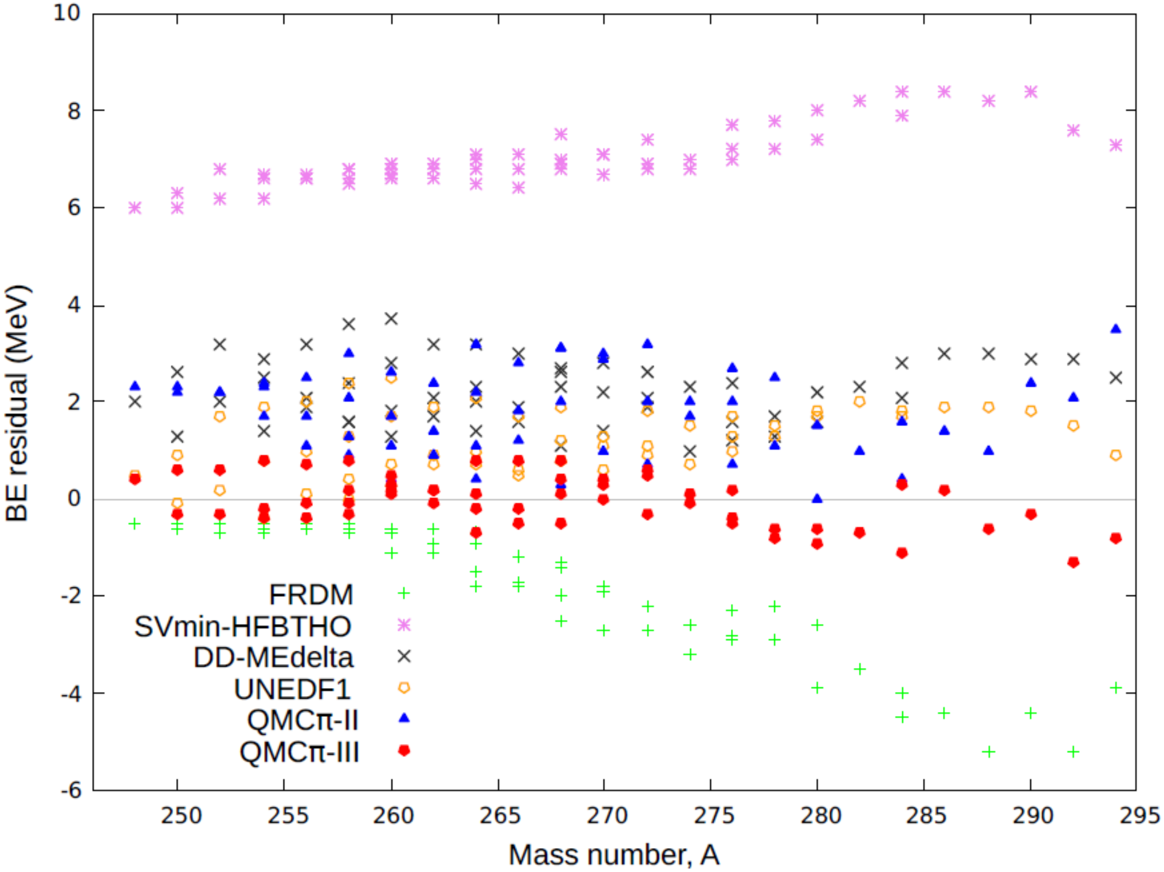
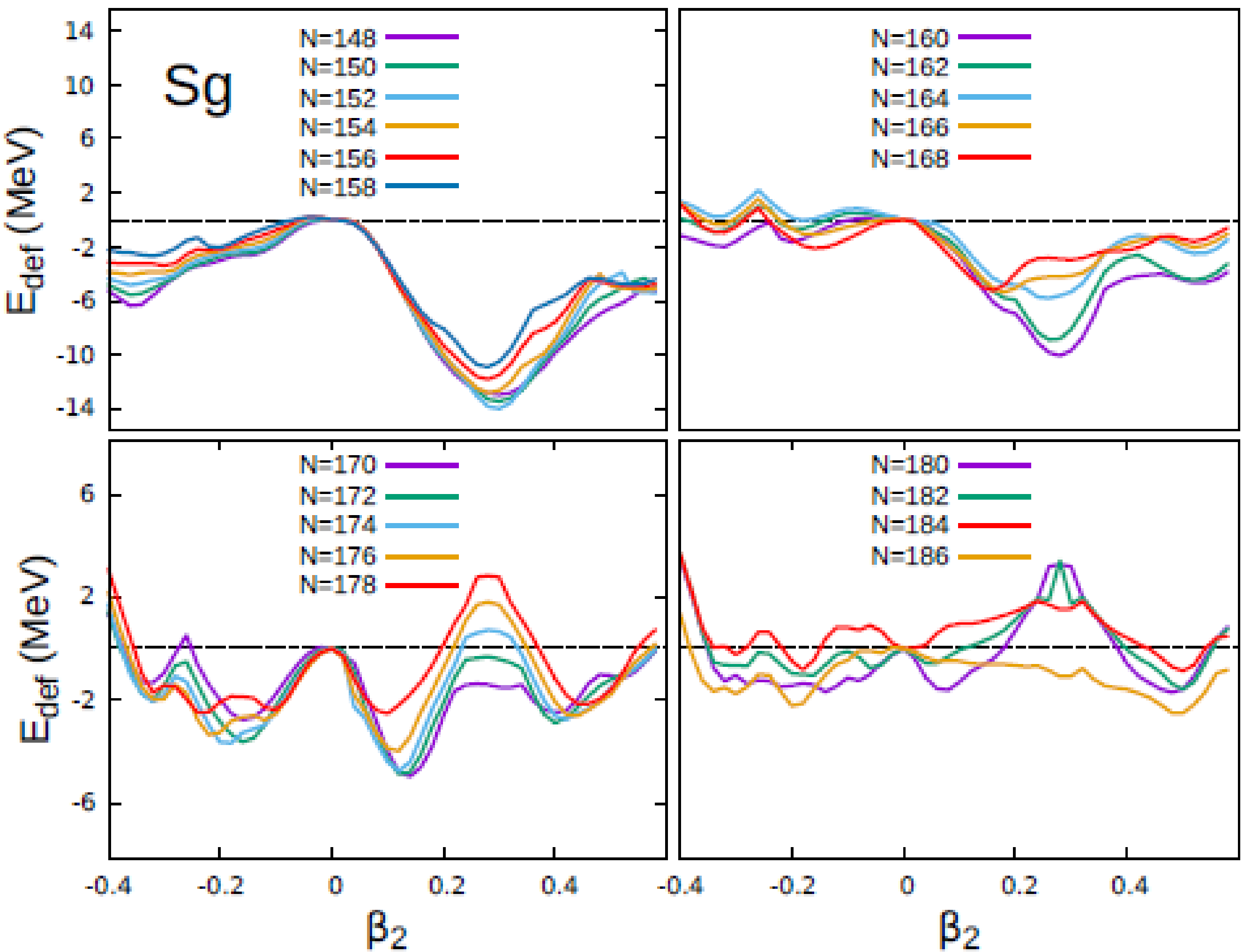


TABLE 6.1: Comparison of *rms* percent deviations and *rms* residuals from QMC and from other nuclear models for SHE with available data.

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

Outstanding agreement

Many Almost Degenerate Minima in Superheavy Region



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Overview of Initial Work on Finite Nuclei

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

- **Has many less parameters but reproduces nuclear properties at a level comparable with the best phenomenological Skyrme forces**

- **Looks like standard nuclear force**

- **BUT underlying theory also predicts modified internal structure and hence modified**
  - **DIS structure functions**
  - **elastic form factors......**

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Nuclear DIS Structure Functions: The EMC Effect

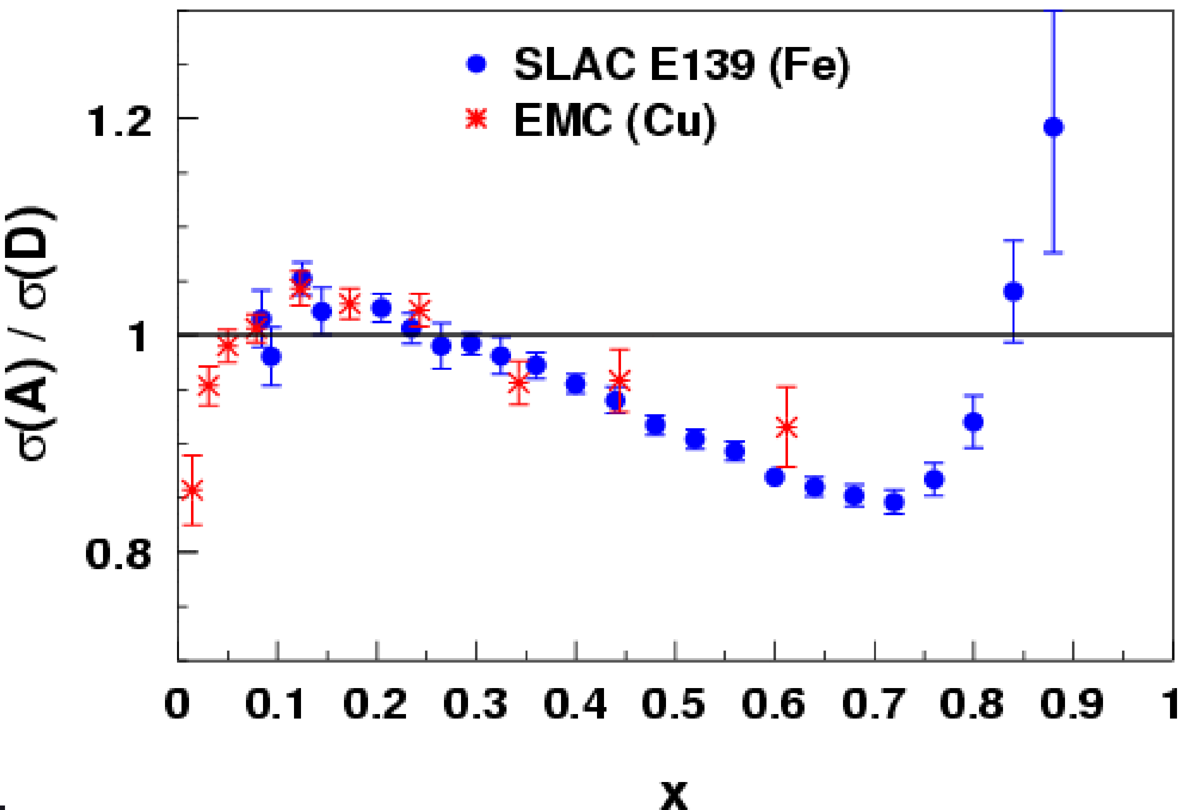
To address questions like this one MUST start with a theory that quantitatively describes nuclear structure and allows calculation of structure functions

– very, very few examples.....

The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the HEP and Nuclear communities 40 years ago

- What is it that alters the quark momentum in the nucleus?



J. Ashman *et al*., Z. Phys. C57, 211 (1993)

J. Gomez *et al*., Phys. Rev. D49, 4348 (1994)

Theoretical Understanding

- Still numerous proposals but few consistent theories

- Initial studies used MIT bag[1] to estimate effect of self-consistent change of structure in-medium
  − but better to use a covariant theory

- For that Bentz and Thomas[2] re-derived change of nucleon structure in-medium in the NJL model

- This set the framework for sophisticated studies by Bentz, Cloët and collaborators over the last decade

[1] Thomas, Michels, Schreiber and Guichon, Phys. Lett. B233 (1989) 43
[2] Bentz and Thomas, Nucl. Phys. A696 (2001) 138

EMC Effect for Finite Nuclei

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

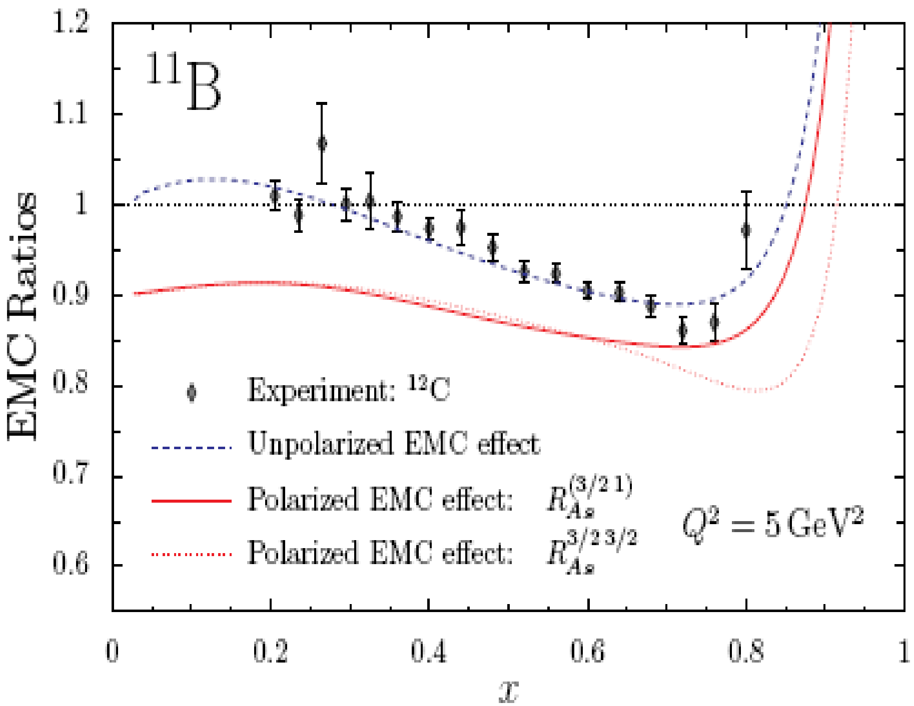


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

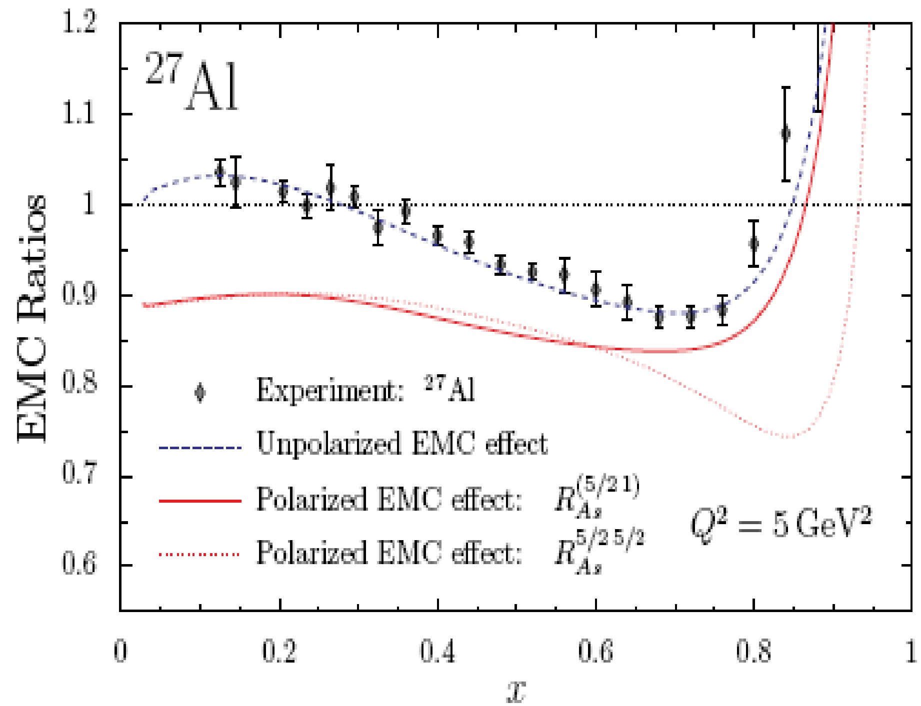
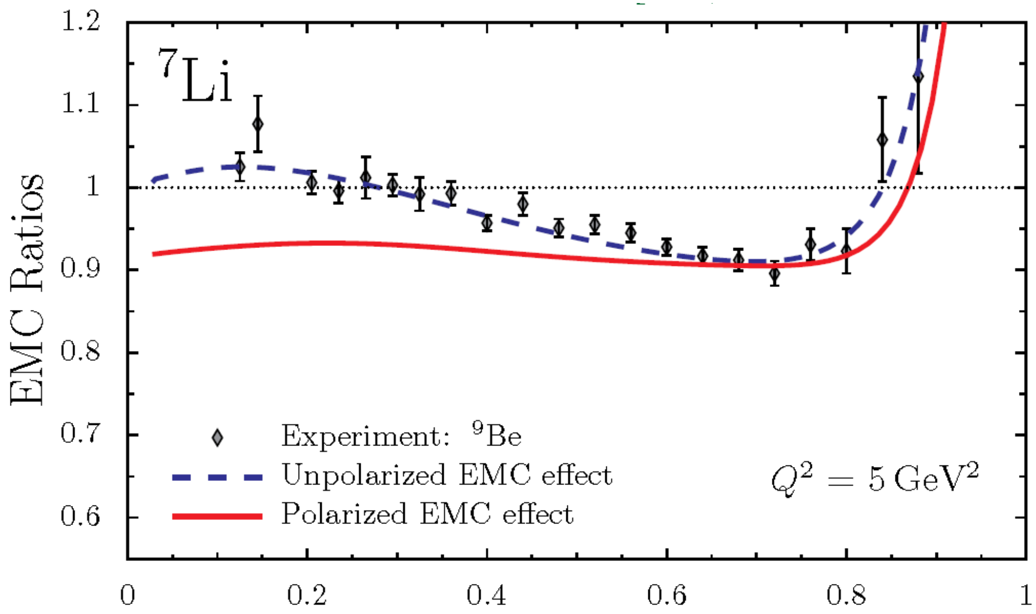


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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

Approved JLab Experiment

- Effect in ^{7}Li is slightly suppressed because it is a light nucleus and proton does not carry all the spin (simple WF: $P_p = 13/15 \quad \& \quad P_n = 2/15$)
- Experiment now approved at JLab [E12-14-001] to measure spin structure functions of ^{7}Li (GFMC: $P_p = 0.86 \quad \& \quad P_n = 0.04$)



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)

For the EIC: Polarized Gluon EMC Effect

Xuangong Wang et al.

J. Phys. G: Nucl. Part. Phys. **49** (2022) 03LT01

Letters

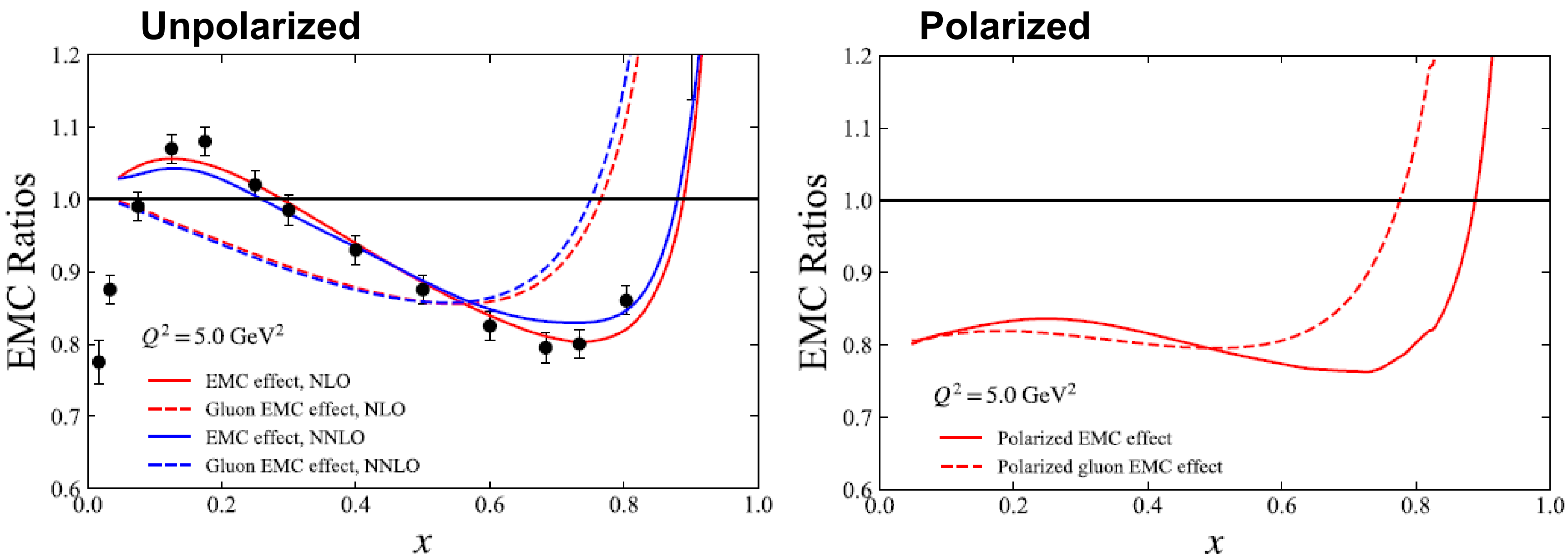


Figure 3. (Left panel) Unpolarized EMC ratios for the structure functions $F_{2A}(x)/F_{2N}(x)$ (solid) and the unpolarized gluon distributions $g_A(x)/g_p(x)$ (dashed). (Right panel) Polarized EMC ratios for the structure functions $g_{1A}(x)/g_{1p}(x)$ (solid) and polarized gluon distributions $\Delta g_A(x)/\Delta g_p(x)$ (dashed). The empirical data points are the unpolarized nuclear matter results for the EMC ratio from reference [53].

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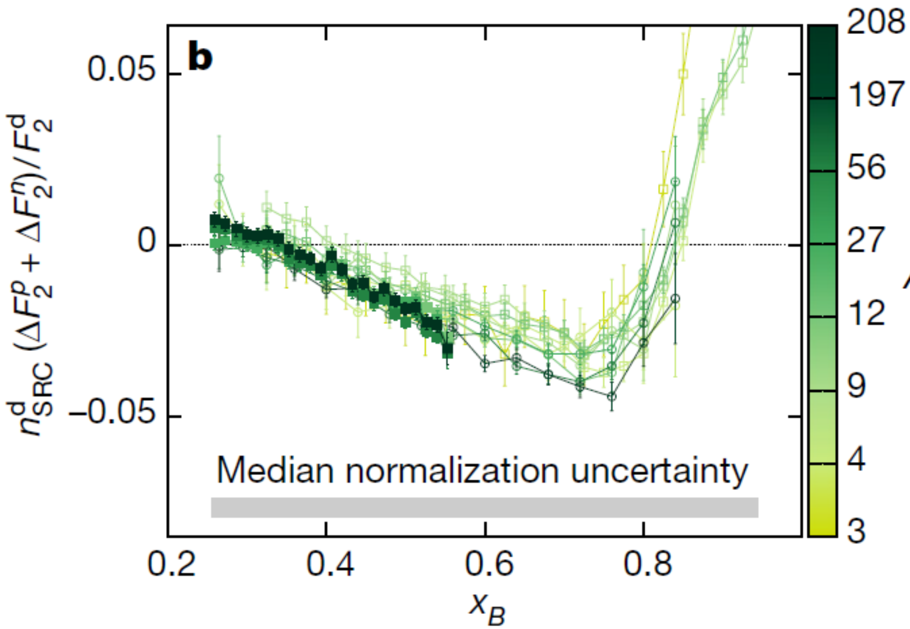
Hypothesis that SRC gives the EMC Effect

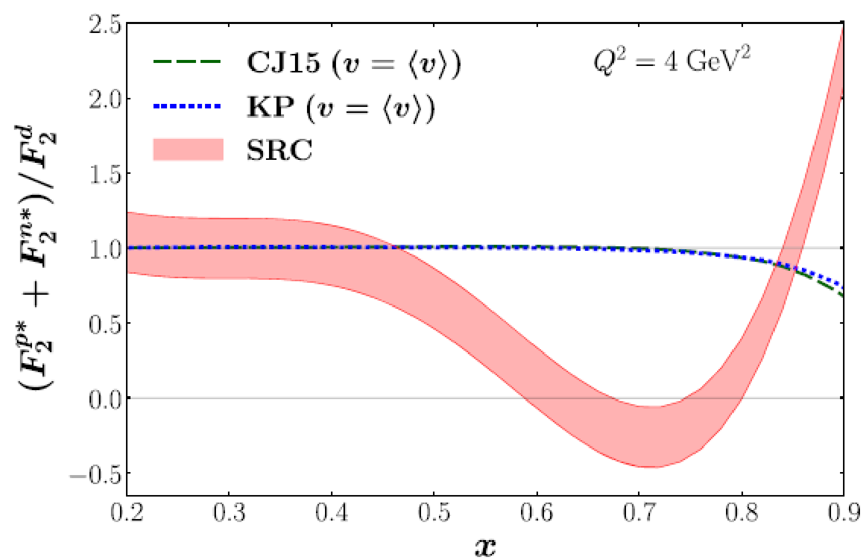
$$F_2^A = (Z - n_{SRC}^A) F_2^p + (N - n_{SRC}^A) F_2^n + n_{SRC}^A (F_2^{p*} + F_2^{n*})$$



Schmookler et al., Nature 566 (2019)

But n^d_{SRC} is only ~0.03

Wang et al., PRL 125 (2020) 262002



Hence huge effect for x>0.5

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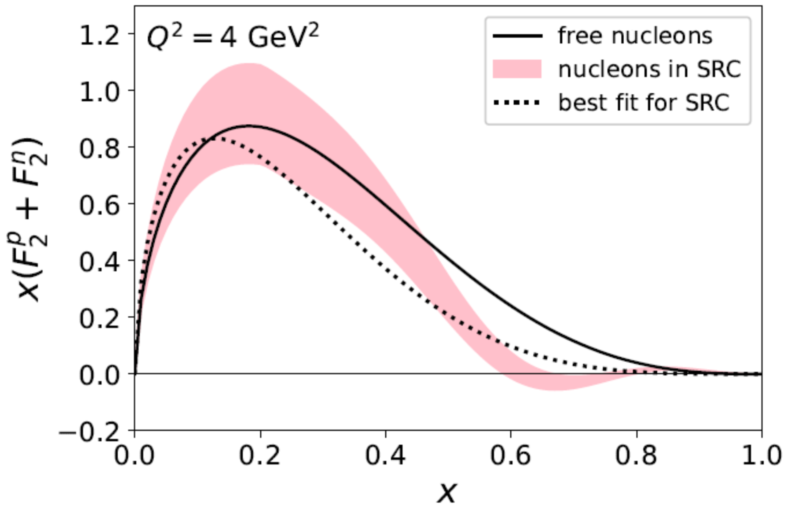
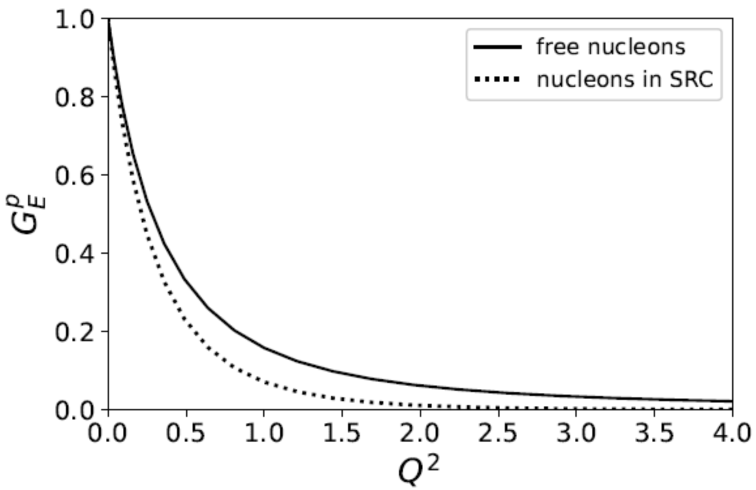
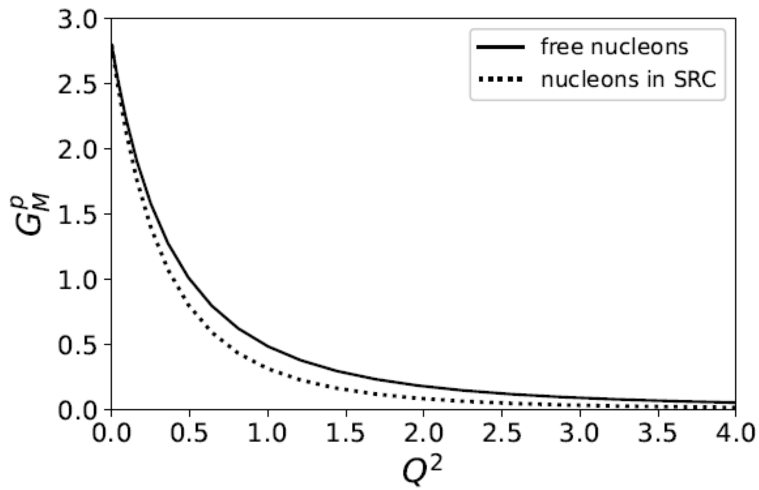
New Observation on SRC and EMC Effect

Use simple AdS/QCD model of Maji and Chakrabati PRD 94 (2016)



Fit SRC-modified F_2 and then calculate modified elastic form factors





Refs: Wang *et al.*, PRL 125 (2020) 262002 and Wanli Xing *et al.*, to be published

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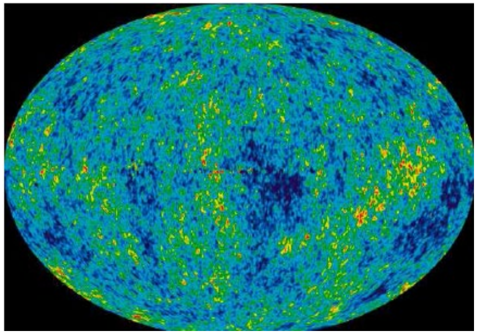
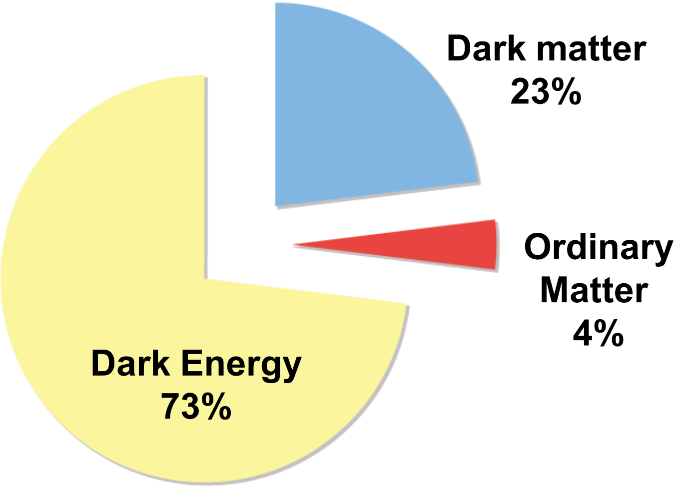
Recent Results Concerning a Dark Photon

Dark Matter and Dark Energy

Over the past two decades we have learnt that,
in spite of the successes of the Standard Model,
most of the matter in the Universe is something else
− Dark Matter

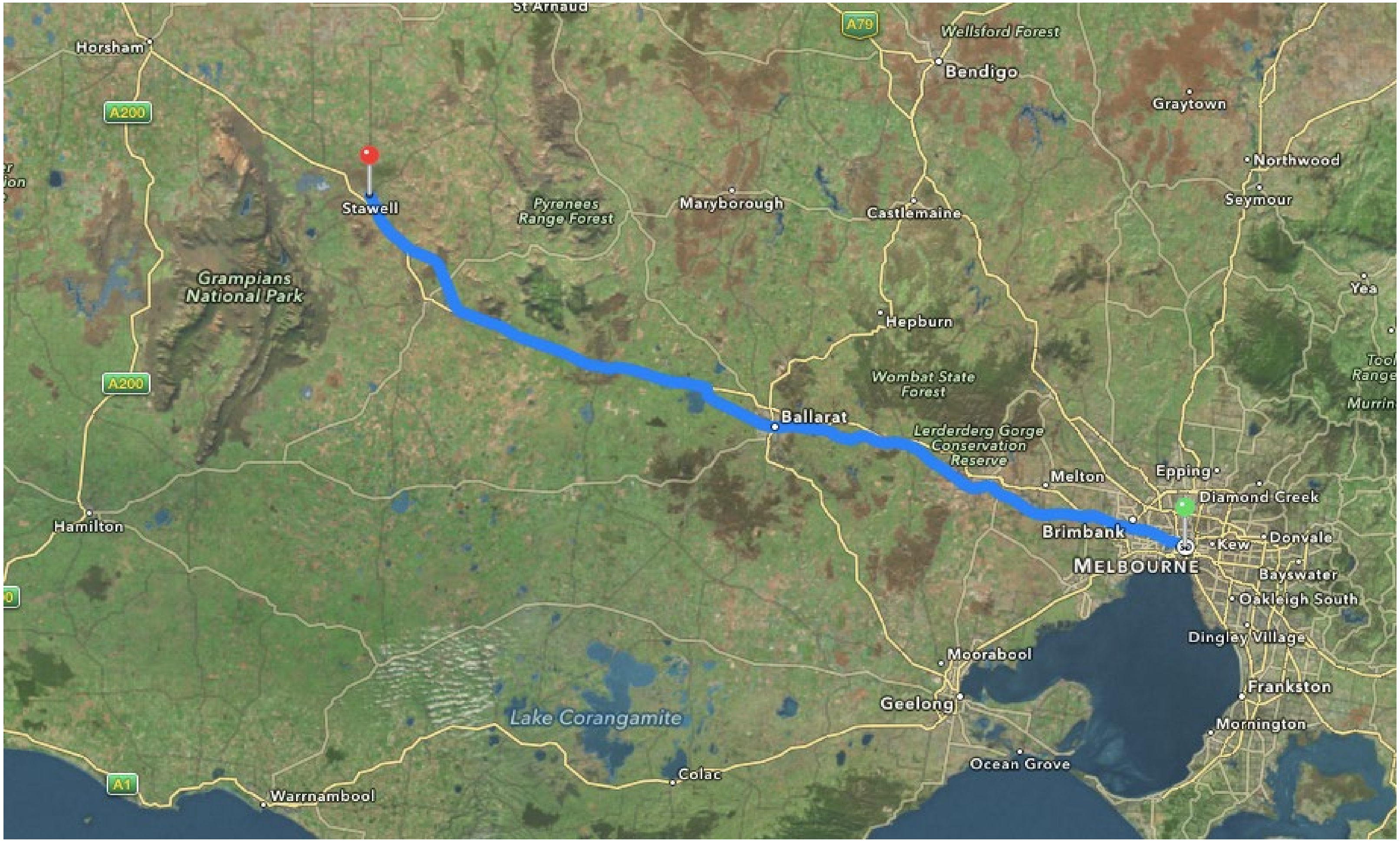




It interacts very weakly but has major gravitational effects

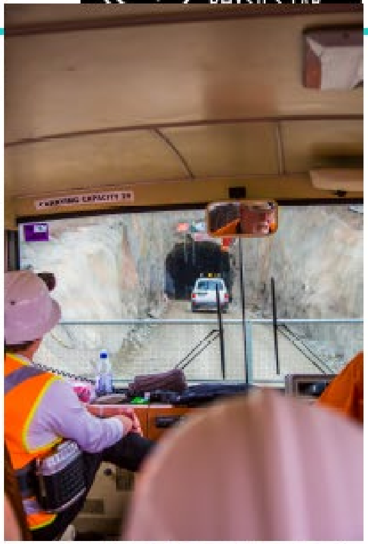
New Underground Laboratory under construction

- Approximately midway between Adelaide and Melbourne
- 1km underground in an active gold mine

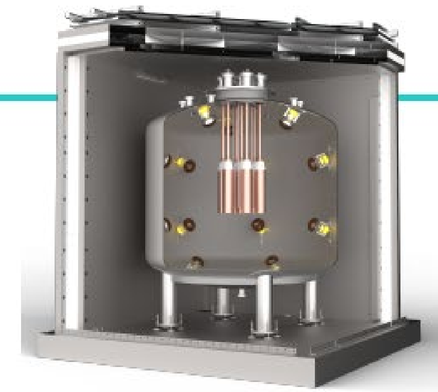


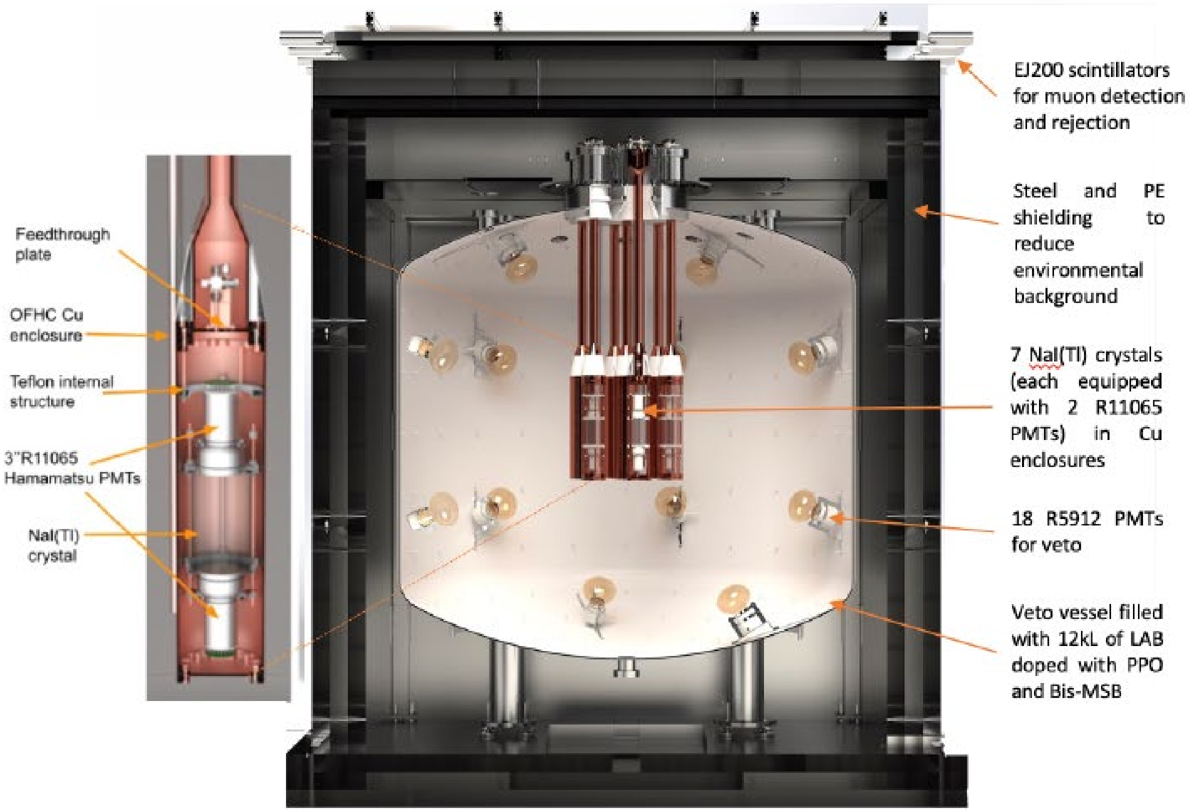
SUPL construction images

STAWELL UNDERGROUND PHYSICS LAB



SABRE Experiment





Evidence for a New BSM Particle?
A Dark Photon

Dark Photon

It is not the solution to DM problem but may be a portal connecting the sectors

- **There are a number of formulations of the dark photon**
- **Initially purely vector couplings, then more like a Z´**
- **For us it is a $U_Y(1)$ boson interacting with Standard Model particles through kinetic mixing**

$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\bar{m}^2_{A'}}{2} A'_\mu A'^\mu + \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$

- **So that the couplings are:**

$$C^v_Z = (\cos\alpha - \epsilon_W \sin\alpha)\bar{C}^v_Z + \epsilon_W \sin\alpha \cot\theta_W C^v_\gamma,$$

$$C^a_Z = (\cos\alpha - \epsilon_W \sin\alpha)\bar{C}^a_Z,$$

and

$$C^v_{A_D} = -(\sin\alpha + \epsilon_W \cos\alpha)\bar{C}^v_Z + \epsilon_W \cos\alpha \cot\theta_W C^v_\gamma,$$

$$C^a_{A_D} = -(\sin\alpha + \epsilon_W \cos\alpha)\bar{C}^a_Z.$$

Dark Photon (cont.)

Where the Standard Model Z couplings are

$$\bar{C}_Z \sin 2\theta_W = T_3^f - 2q_f \sin^2\theta_W, \qquad \bar{C}_Z^a \sin 2\theta_W = T_3^f$$

and the mixing parameters are

$$\tan\alpha = \frac{1}{2\epsilon_W}\Big[1 - \epsilon_W^2 - \rho^2 - \text{sign}(1-\rho^2)\sqrt{4\epsilon_W^2 + (1-\epsilon_W^2-\rho^2)^2}\Big]$$

and

$$\epsilon_W = \frac{\epsilon \tan\theta_W}{\sqrt{1-\epsilon^2/\cos^2\theta_W}}$$

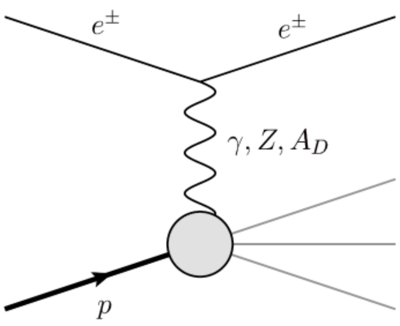
$$\rho = \frac{\bar{m}_{A'}/\bar{m}_{\bar{Z}}}{\sqrt{1-\epsilon^2/\cos^2\theta_W}}$$

with ε the mixing parameter in the Lagrangian

New JAM Analysis of World Data

Following earlier work of Wang and Thomas

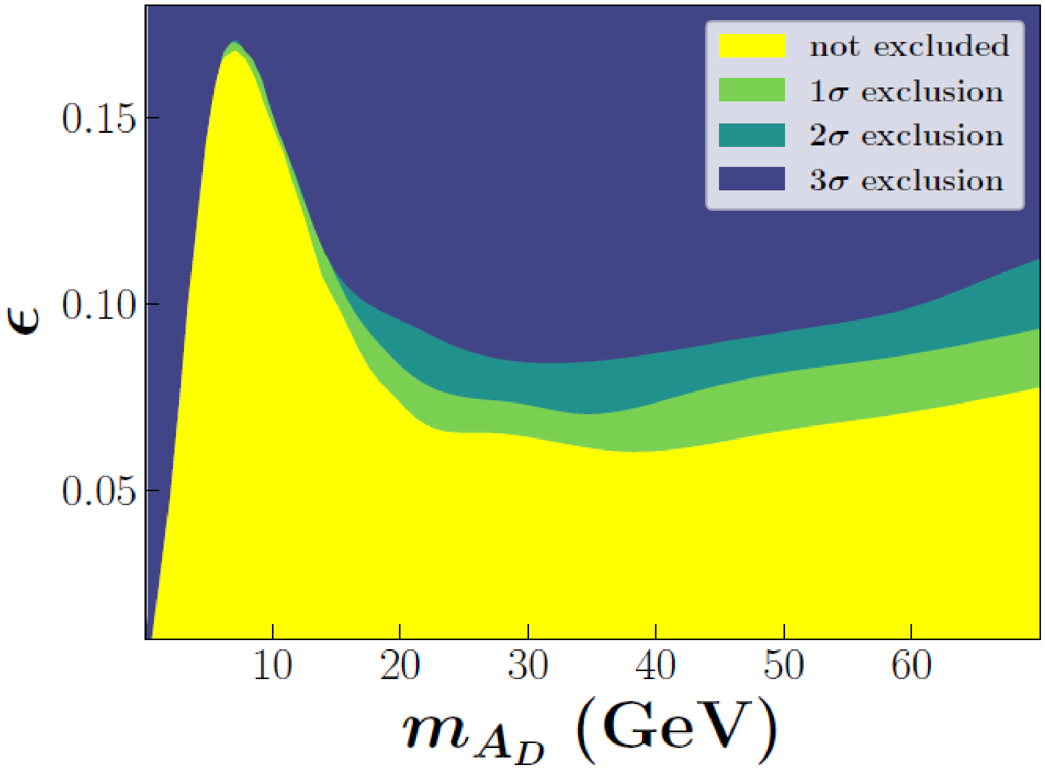
J. Phys. G: Nucl. Part. Phys. 47 (2020) 015102



Use JAM Framework to Analyse World Data to determine Exclusion Limits

Hunt-Smith *et al., arXiv2302.11126*

- NLO analysis with $Q^2 > 1.69\ \mathrm{GeV}^2$ and $W^2 > 10\ \mathrm{GeV}^2$
- Over 3,000 fixed target and HERA data

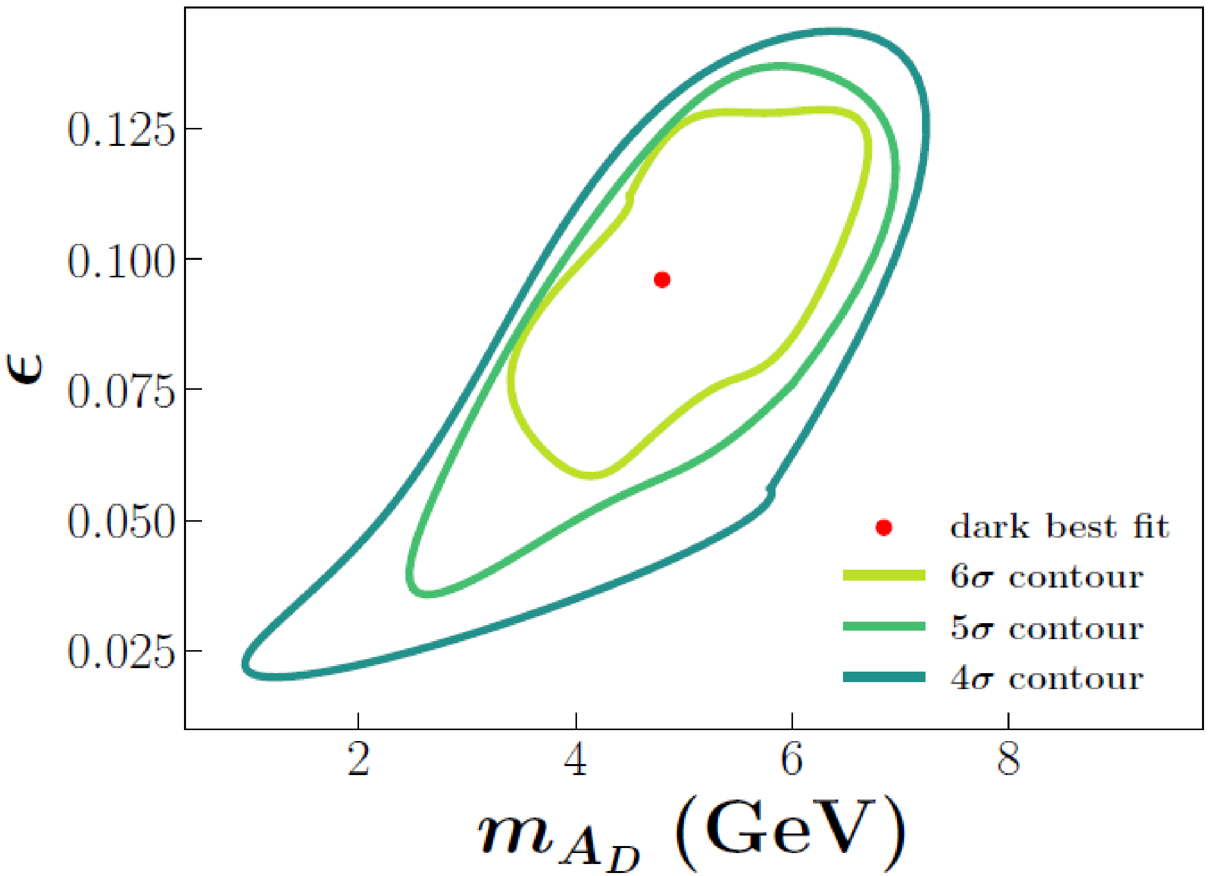


BUT if we accept that a dark photon may exist

X^2 analysis strongly prefers it!

reaction	χ^2_{dof}(dark)	χ^2_{dof}(base)	N_{dof}
fixed target DIS	1.01	1.05	1495
HERA NC	1.02	1.03	1104
HERA CC	1.13	1.18	81
Drell-Yan	1.18	1.16	205
Z rapidity	1.08	1.05	56
W asymmetry	1.04	1.07	97
jets	1.16	1.15	200
total	1.03	1.05	3283

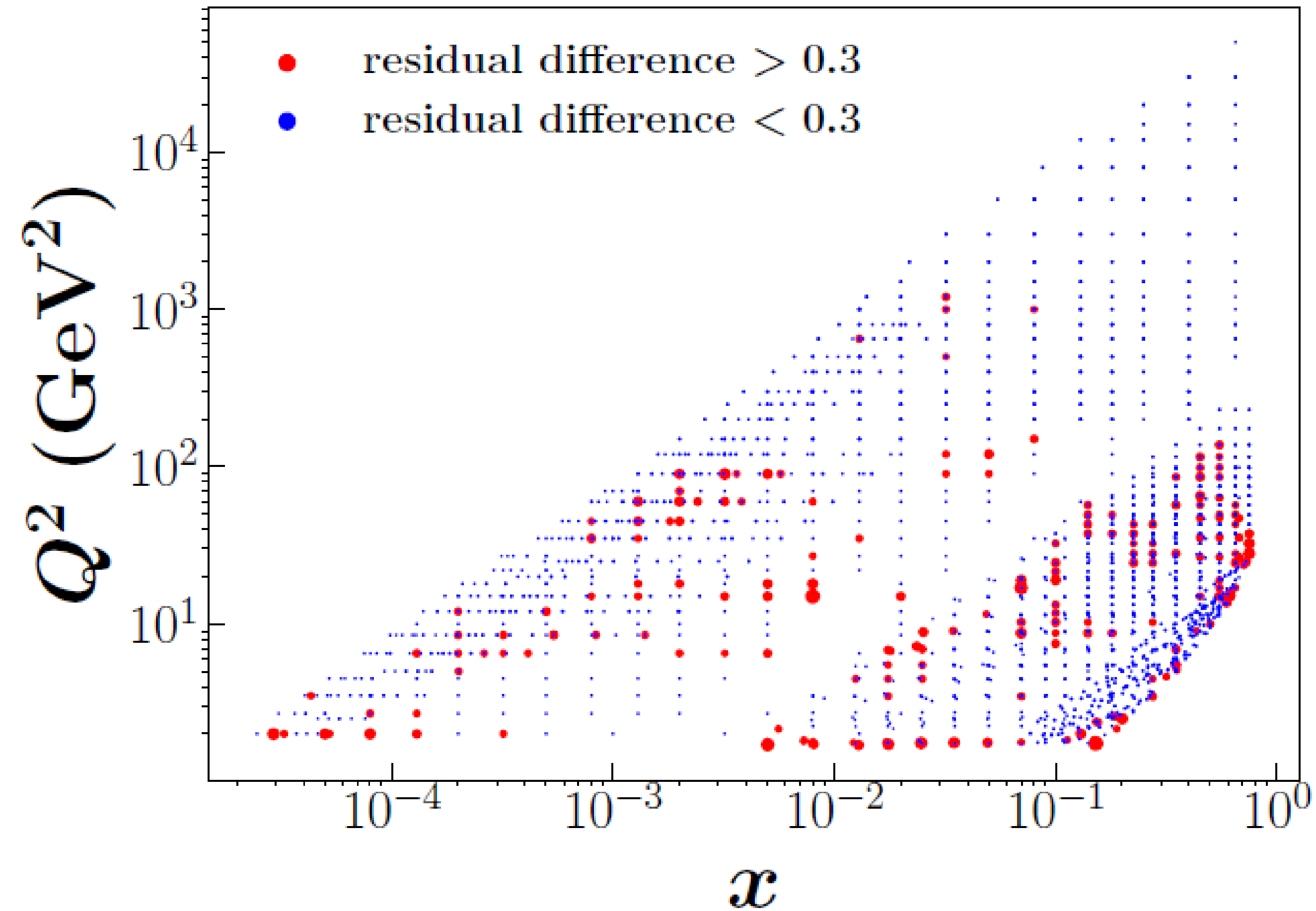
Hypothesis that SM is correct EXCLUDED at 6.5 σ



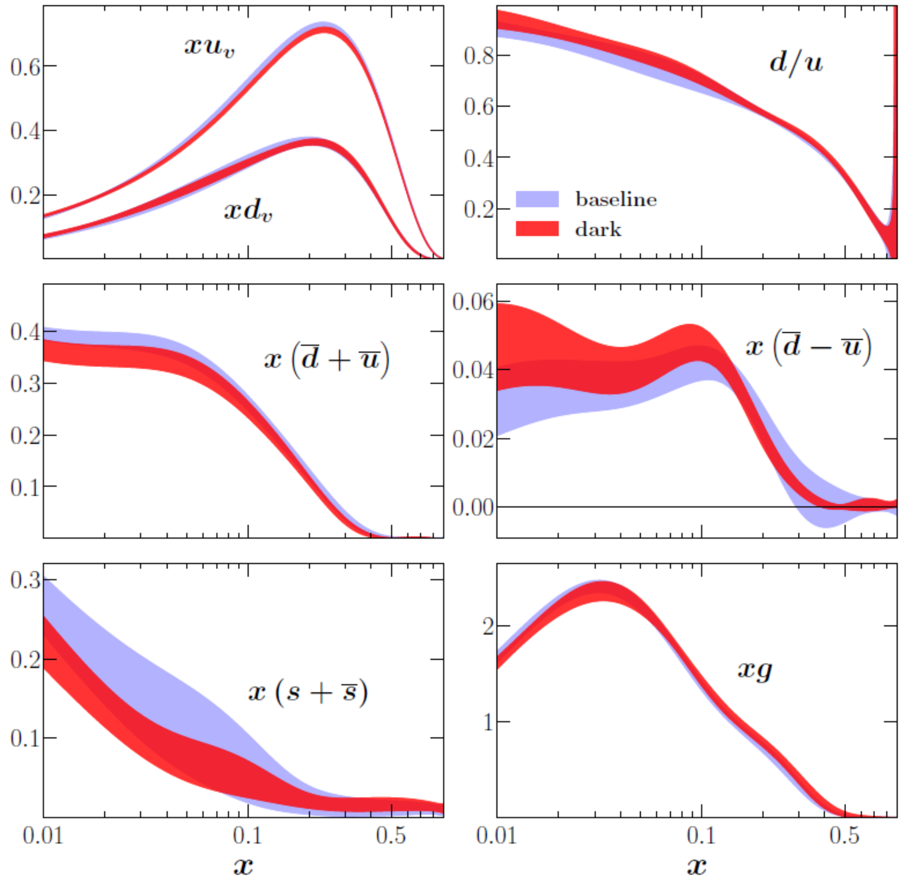
Stable against omission of HT corrections and increase of lower Q^2 cut to 10 GeV^2

Hunt-Smith *et al.*, *arXiv2302.11126*

Improvement over full range of Q^2 and x

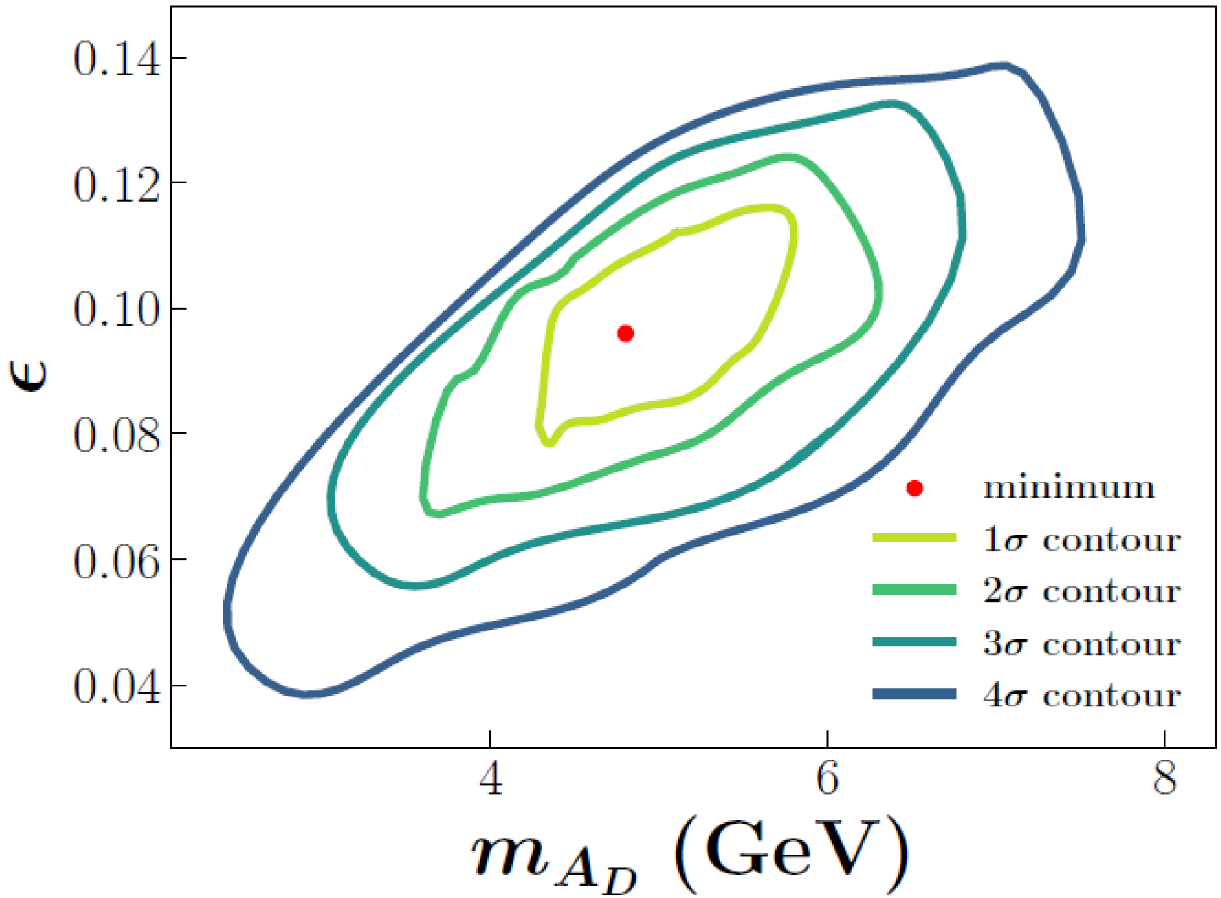


PDFs consistent with NO DP Analysis



Uncertainties based on analysis with 200 replicas

Best fit parameters



Hunt-Smith *et al.*, *arXiv2302.11126*

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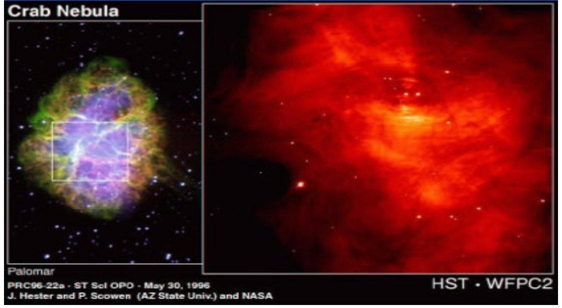
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

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

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SUB CRUCE LUMEN

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

II. Summary

- Need empirical confirmation of changing baryon structure:
  - Response Functions & Coulomb sum rule
  - EMC effect; spin EMC (not too long…)
  - Change in Λ decay rate in nuclei?

- Initial systematic study of finite nuclei very promising

  With just 5 parameters:

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

- Finally, we showed an exciting hint of the existence of a new BSM particle in the mass region 1-8 GeV

Special Mentions……

Guichon

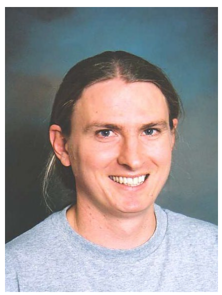
Tsushima

Saito

Stone

Krein

Matevosyan



Cloët

Whittenbury

Simenel

Bentz

Martinez

Motta

Antic

Kalaitzis

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DARK MATTER

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Latest papers

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

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

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

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

Key papers on QMC

- **Many-body forces:**
  1. Guichon, Matevosyan, Sandulescu, Thomas, Nucl. Phys. A772 (2006) 1.
  2. Guichon and Thomas, Phys. Rev. Lett. 93 (2004) 132502

- **Built on earlier work on QMC: e.g.**
  3. Guichon, Phys. Lett. B200 (1988) 235
  4. Guichon, Saito, Rodionov, Thomas, Nucl. Phys. A601 (1996) 349

- **Major review of applications of QMC to many nuclear systems:**
  5. Saito, Tsushima, Thomas, Prog. Part. Nucl. Phys. 58 (2007) 1-167 (hep-ph/0506314)
  6. Guichon et al., Prog. Part. Nucl. Phys. 100 (2018) 262

References to: Covariant Version of QMC

- Basic Model: (Covariant, chiral, confining version of NJL)

- Bentz & Thomas, Nucl. Phys. A696 (2001) 138
- Bentz, Horikawa, Ishii, Thomas, Nucl. Phys. A720 (2003) 95

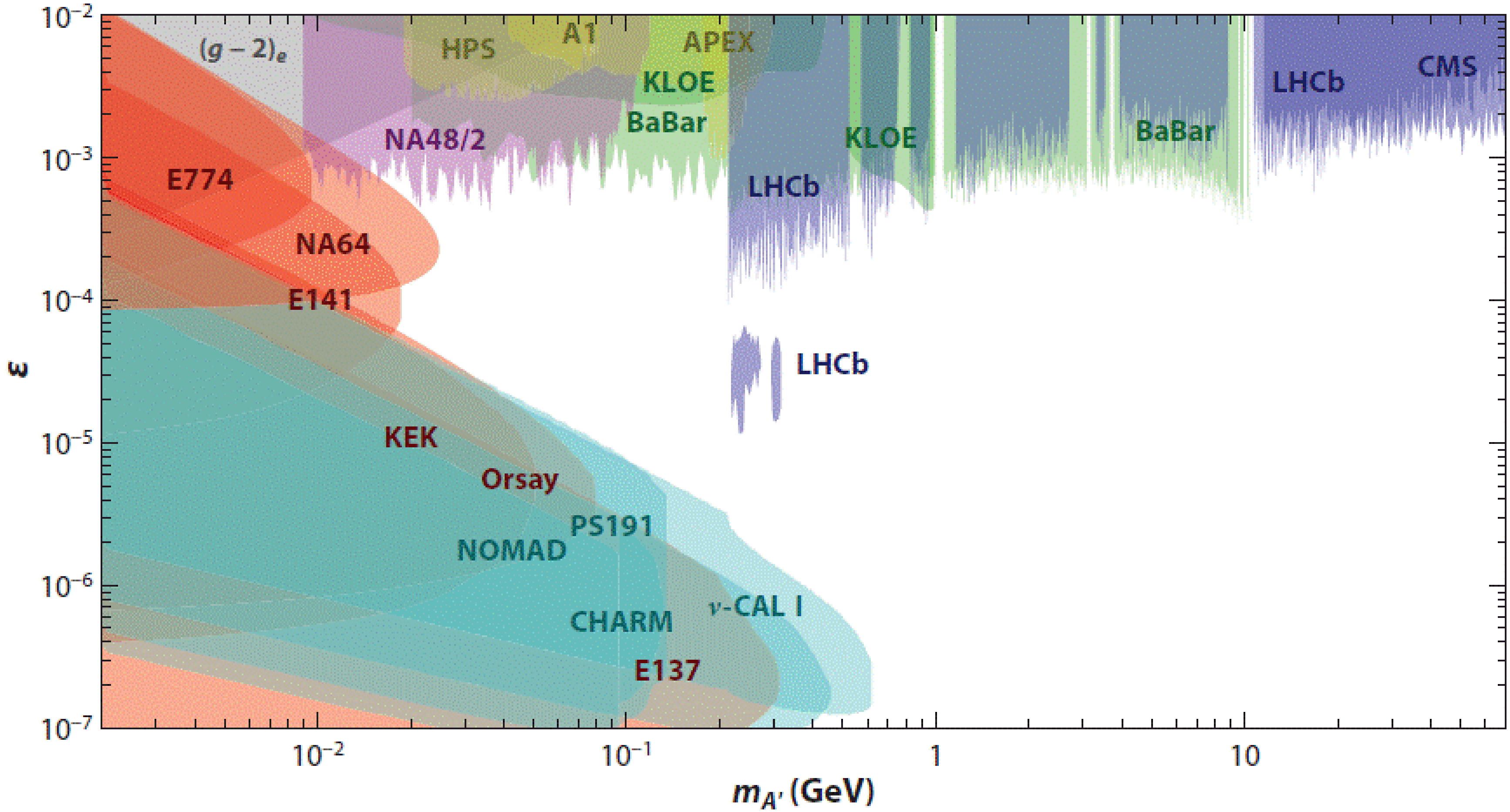
- Applications to DIS:

- Cloet, Bentz, Thomas, Phys. Rev. Lett. 95 (2005) 052302
- Cloet, Bentz, Thomas, Phys. Lett. B642 (2006) 210

- Applications to neutron stars – including SQM:

- Lawley, Bentz, Thomas, Phys. Lett. B632 (2006) 495
- Lawley, Bentz, Thomas, J. Phys. G32 (2006) 667

Experimental Constraints



From Graham et al., Annu. Rev. Nucl. Part. Sci. 71 (2021) 37

Very large scalar mean-fields are a fact

1970 R. BROCKMANN AND R. MACHLEIDT

TABLE II. Results of a relativistic Dirac-Brueckner calculation in comparison to the tential B. As a function of the Fermi momentum k_F, it is listed: the energy per nucleon vector potentials U_S and U_V, and the wound integral κ.

		Relativistic			
k_F (fm^{-1})	$\mathcal{E}/A$ (MeV)	$\tilde{M}/M$	U_S (MeV)	U_V (MeV)	κ (%)
0.8	−7.02	0.855	−136.2	104.0	23.1
0.9	−8.58	0.814	−174.2	134.1	18.8
1.0	−10.06	0.774	−212.2	164.2	16.1
1.1	−11.18	0.732	−251.3	195.5	12.7
1.2	−12.35	0.691	−290.4	225.8	11.9
1.3	−13.35	0.646	−332.7	259.3	12.5
1.35	−13.55	0.621	−355.9	278.4	13.0
1.4	−13.53	0.601	−374.3	293.4	13.8
1.5	−12.15	0.559	−413.6	328.4	14.4
1.6	−8.46	0.515	−455.2	371.0	15.8

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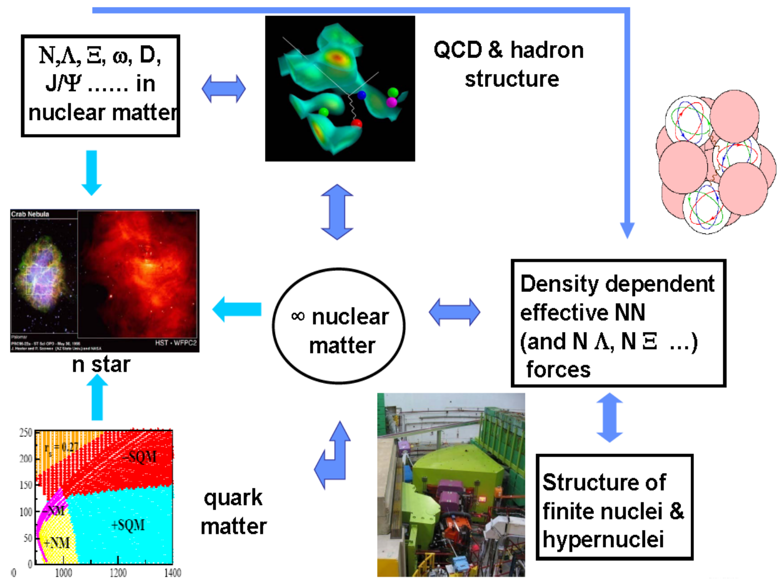
Brockmann and Machleidt, Phys Rev C52 (1990) 1965

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Suggests a different approach : QMC Model

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

- **Start with quark model (MIT bag/NJL...) for all hadrons**



- **Introduce a relativistic Lagrangian with σ, ω and ρ mesons coupling to non-strange quarks**

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

  $(m_\sigma , g^{\sigma,\omega,\rho}{}_q)$

  − determine by fitting to:

  ρ_0 , E/A and symmetry energy

  − same in dense matter & finite nuclei

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

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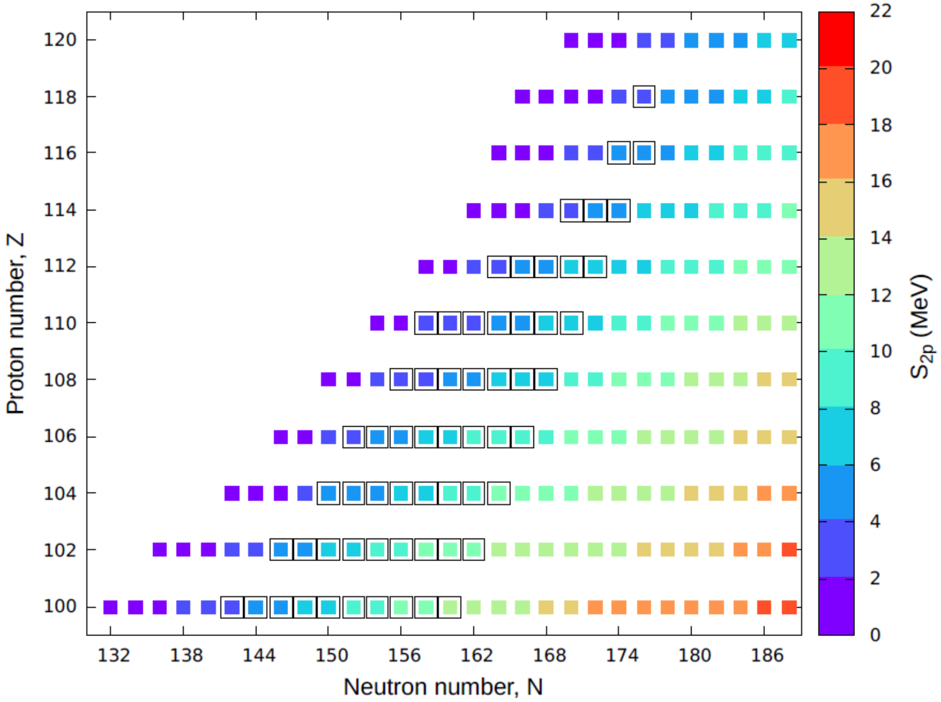
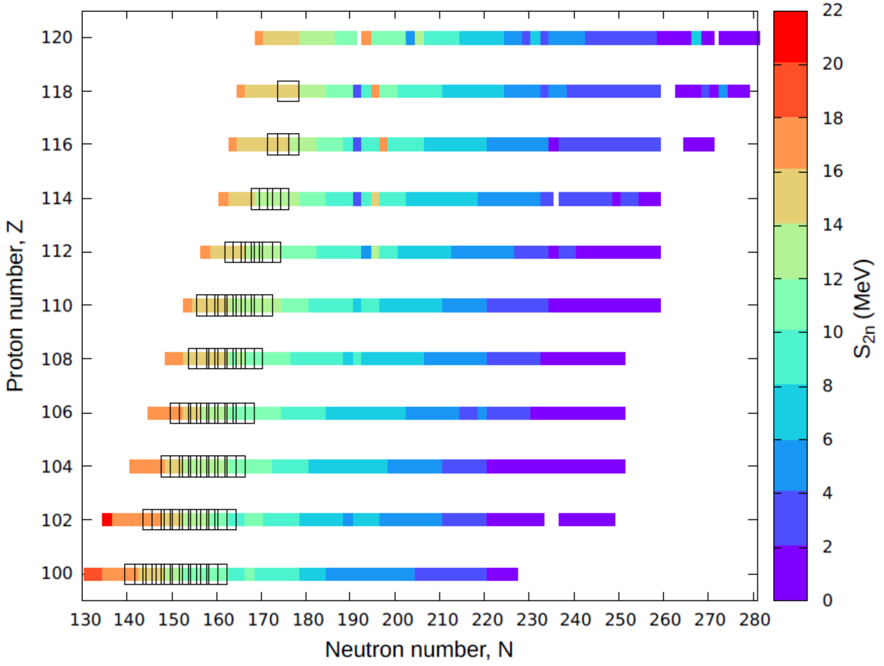
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Proton and Neutron Drip Lines





α Decay Half-Lives

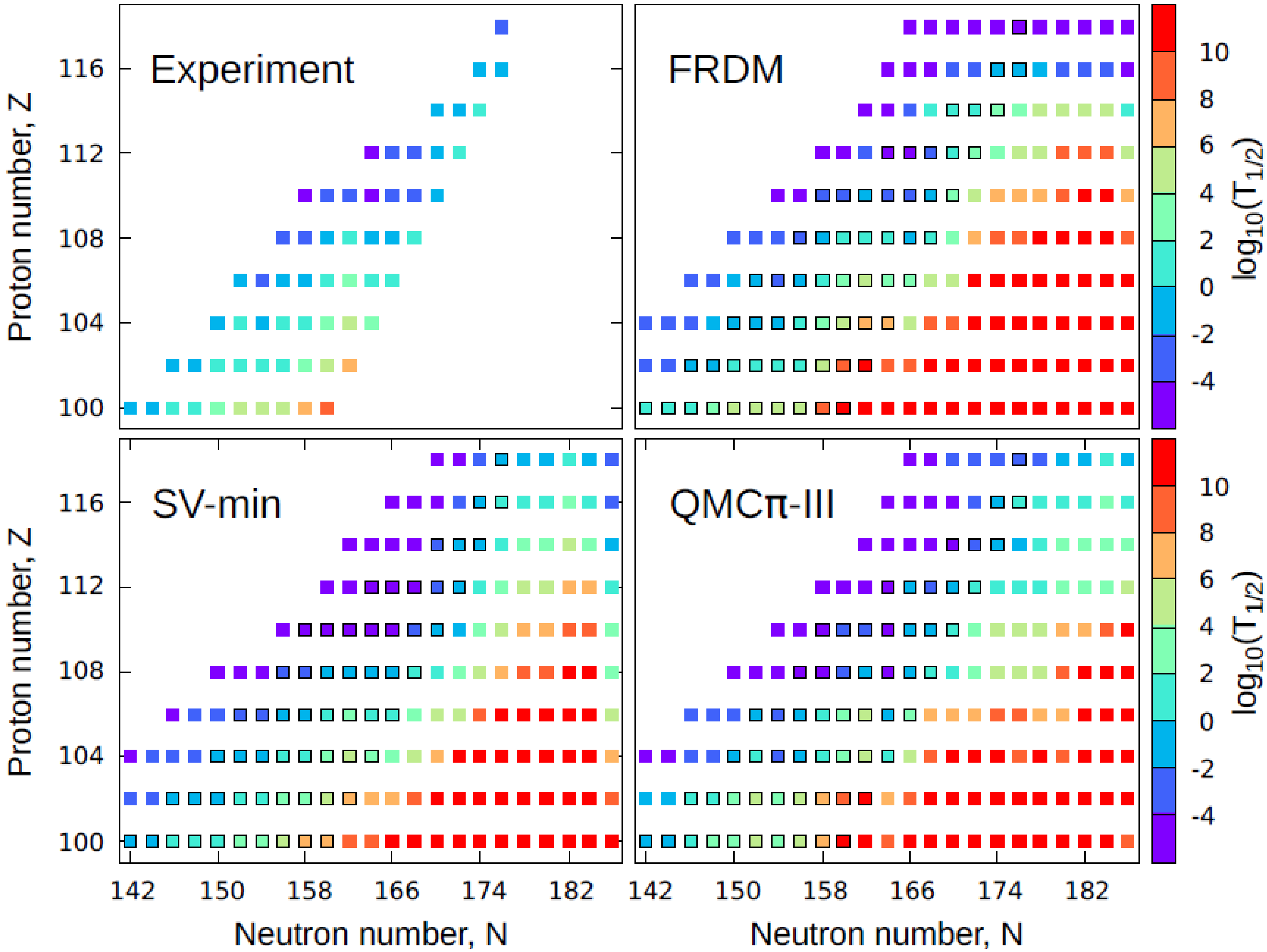


FIGURE 6.10: Comparison of $\log_{10}(T_{1/2})$ predictions from FRDM, SV-min and QMCπ-III along with values obtained from available data.

Not as good as UNDEF1 and SV-min comparable to FRDM

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

Also predicts Ξ – hypernuclei bound by 5-15 MeV – being tested at J-PARC

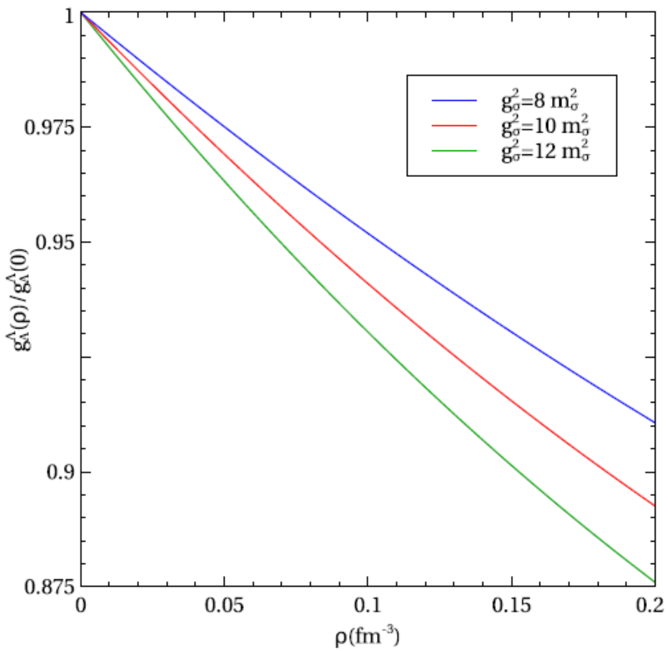
"The first evidence of a bound state of Ξ^{-} ^{14}N system",
K. Nakazawa et al.,
Prog. Theor. Exp. Phys. (2015)

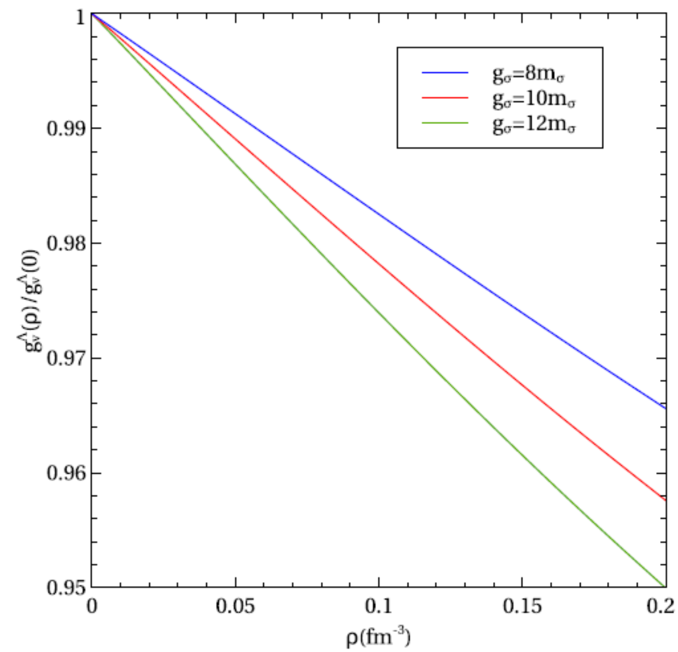
Guichon *et al.*, Nucl.Phys. A814 (2008) 66; see also 1998

Change in Structure of Bound Λ

- **Effect of the σ mean field is to modify the wave functions of the light quarks in the N**

- **Hence, the rates of vector and axial vector strangeness changing weak decays change in-medium**





Guichon & Thomas, Phys Lett B773 (2017) 332