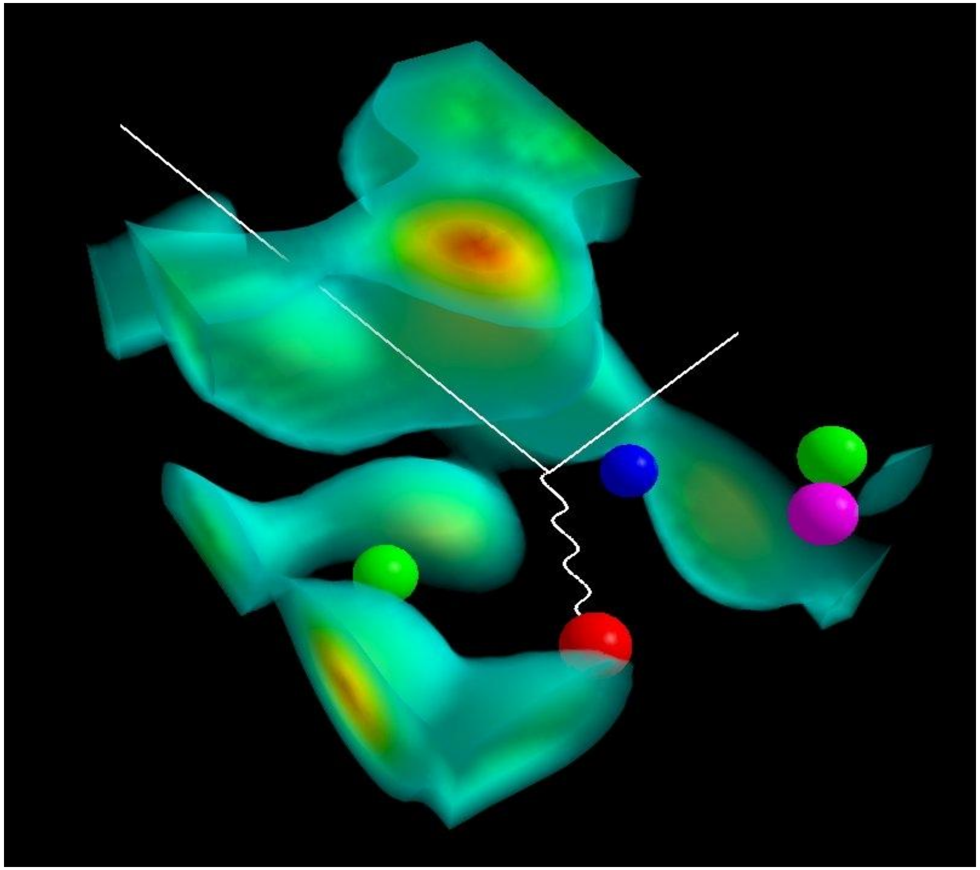
From Hadron to Nuclear Structure



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Anthony W. Thomas

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Hadrons and Hadron Interactions in QCD
Yukawa Institute – Kyoto University : Feb 23rd 2015

SPECIAL RESEARCH
CENTRE FOR THE
SUBATOMIC
STRUCTURE OF MATTER

The Issues

- **A *new approach* to nuclear structure?**

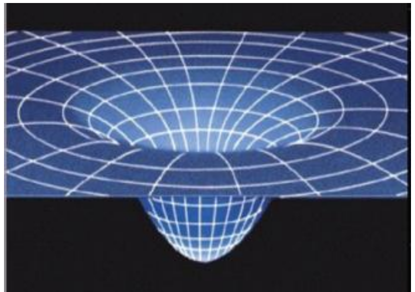
- **Start from a QCD-inspired model of *hadron* structure**

- **Ask how that structure is modified in-medium**

- **This naturally leads to saturation**
  + predictions for all hadrons

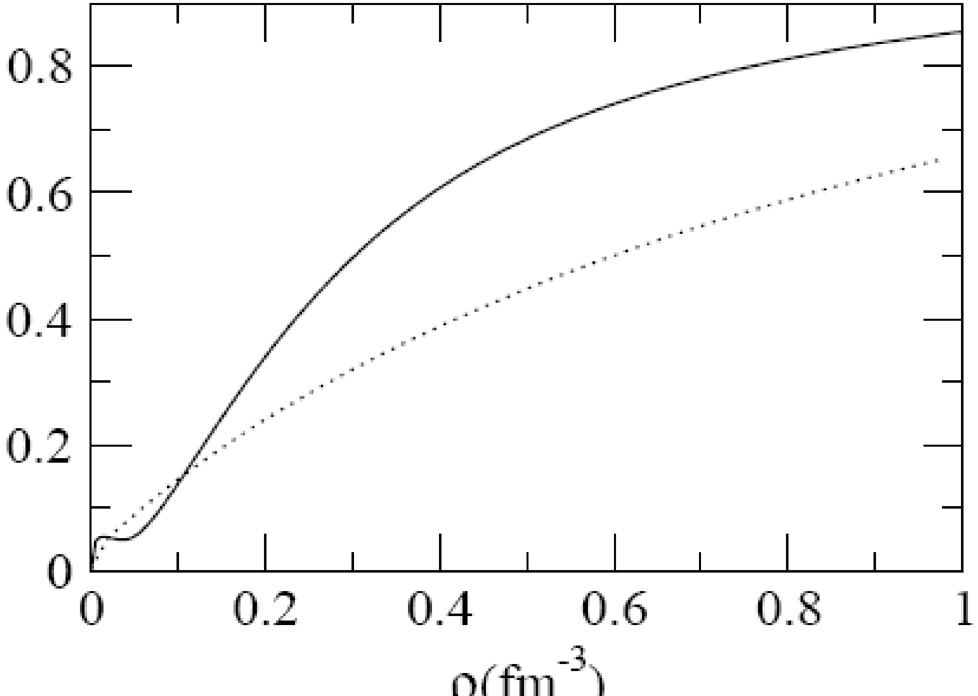
- **Fit n-p matter:**
  ρ_0 , E/A , symmetry energy, compressibility etc.

- **Predict dense matter; hyper-nuclei; finite nuclei**



Relativity

- In n-star core densities > 2-3 ρ_0 : must have a relativistic EoS
  - $p_F^n \sim m^*_n$
  - e.g. velocity of sound:



Hyperons in Dense Matter?

- Baryons in medium are not complicated – in a sense

- E_H (p) – E_N (p) ~ constant (not Σ-N)

  − Λ – N ~ 170 MeV
  − Ξ – N ~ 380 MeV but $\mu_{e/muon}$ ~ 230 – 250 MeV max.
  which means Ξ^- competes with Λ

- Clearly, as p_F^n increases Λ or Ξ^- <u>must</u> enter

  − typically around 3 ρ_0

- Effect is obviously to soften EoS

Summary:

We need a relativistic EoS including hyperons

Where to get the interactions?

- **Familiar approach**:

  − Fit NN interaction to NN data – typically 20-30 parameters to fit 1000's of data points

  − BUT to fit nuclear data also need 3-body force: typically 4 parameters fit to energy levels light nuclei

- **ΛN** : very limited data plus systematic Λ-hypernuclei

  − cannot determine 20-30 parameters of a "realistic" potential and certainly no 3-body force!

Interactions (cont.)

- **Σ N** : no elastic data. Few dozen data on ΛN −> ΣN

  − Contrary to first results in early 80’s there are
  no Σ – hypernuclei (one exceptional, very light case)

  − Phenomenologically :
  Σ – nucleus interaction is somewhat repulsive

- **Ξ N** : No elastic data.

  Nothing known about Ξ – hypernuclei BUT at J-PARC
  experimental study just beginning

- **H H** : Nothing known empirically

Suggests a different approach : QMC Model

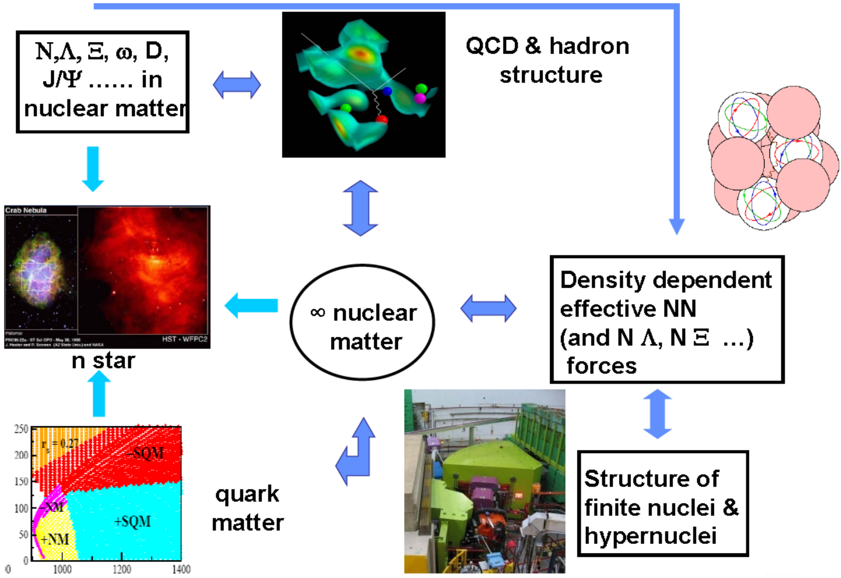
(Guichon, Saito, Tsushima et al., Rodionov et al.
- see Saito et al., Prog. Part. Nucl .Phys. 58 (2007) 1 for a review)

- 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)



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

QCD & hadron structure

n star

∞ nuclear matter

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

quark matter

Structure of finite nuclei & hypernuclei

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

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

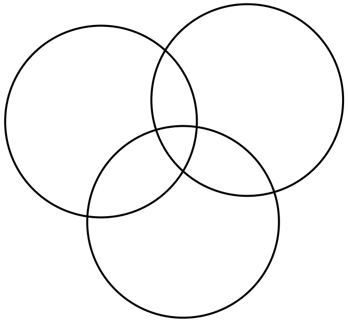
d ~ 0.22 R in original QMC (MIT bag)

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.

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:



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

– same is true in nuclear physics

Summary so far .....

- QMC looks superficially like QHD but it’s fundamentally different from *all* other approaches

- Self-consistent adjustment of hadron structure opposes applied scalar field (“scalar polarizability”)

- Naturally leads to saturation of nuclear matter
  − effectively because of natural 3- and 4-body forces

- Only 3- 4 parameters: σ, ω and ρ couplings to light quarks (4th because m_σ ambiguous under quantisation)

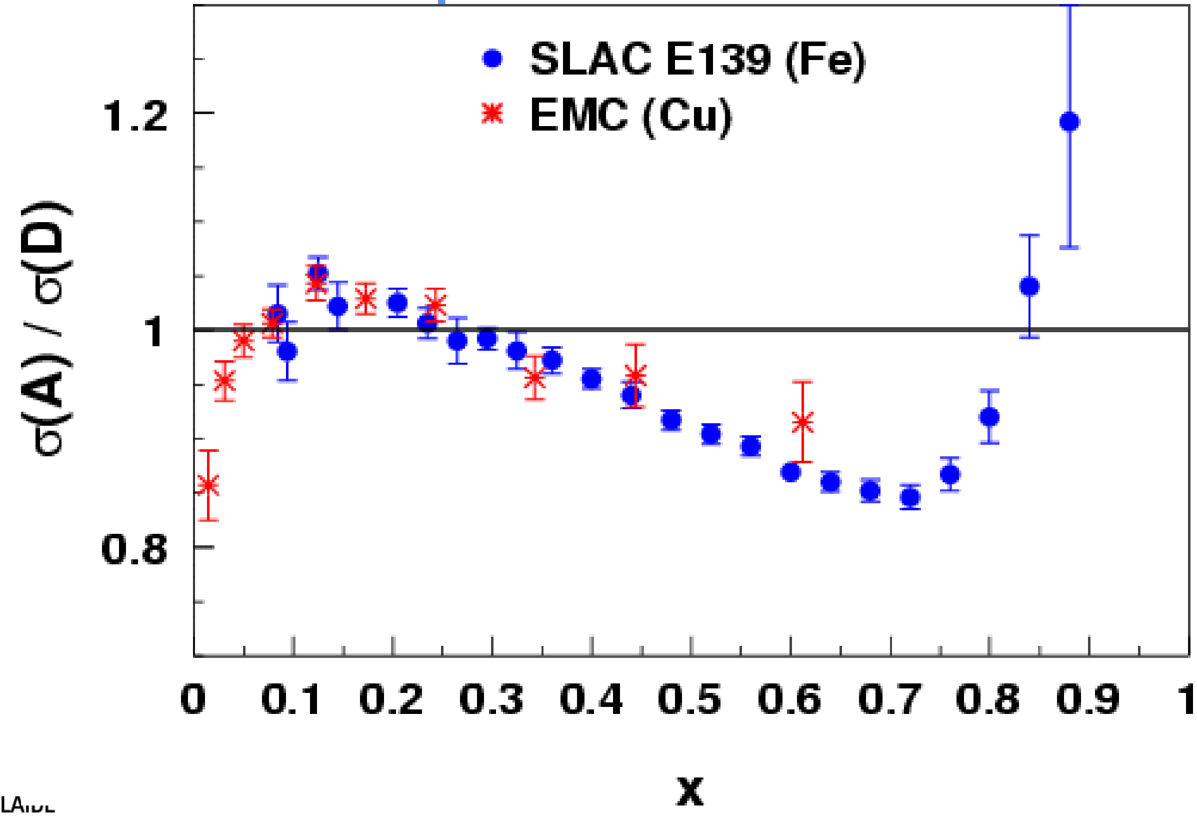
- Fit to nuclear matter properties and then *predict* the interaction of <u>any</u> hadrons <u>in-medium</u>

The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the
  HEP and Nuclear communities 20 years ago

- Nearly 1,000 papers have been generated…..

- 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)

Calculations for Finite Nuclei

(Spin dependent EMC effect TWICE as large as unpolarized)

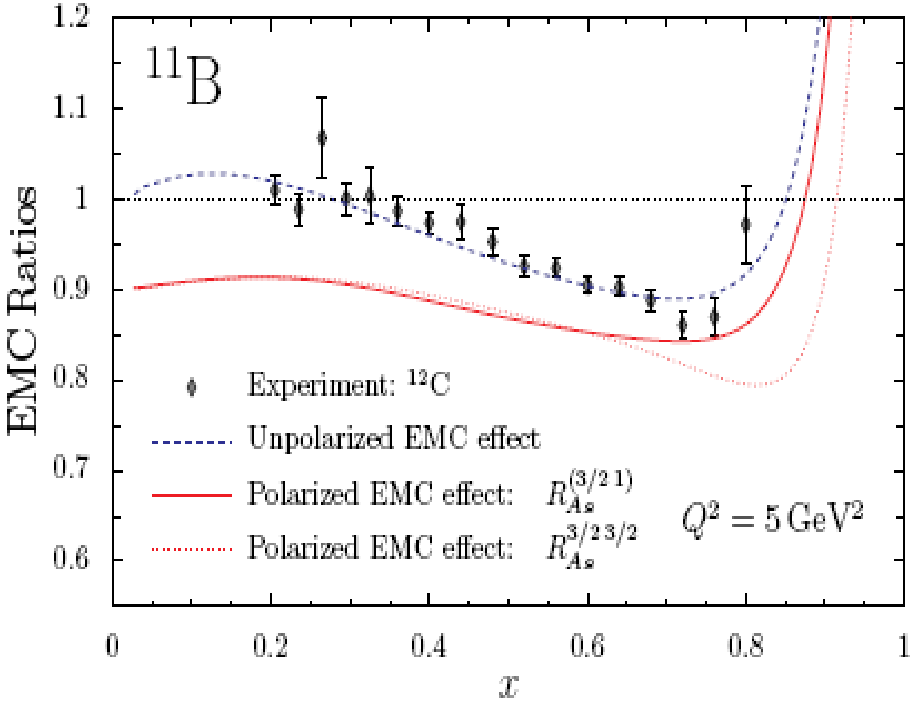


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

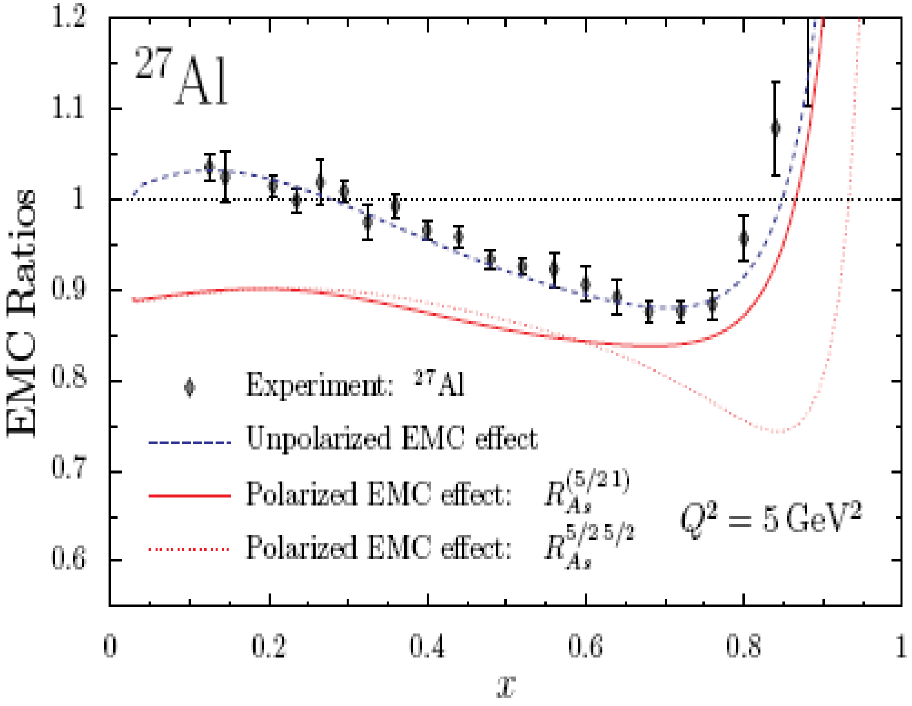


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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

Linking QMC to Familiar Nuclear Theory

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**

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

explicitly obtained effective force, 2- plus 3- body, of Skyrme type

- <u>density-dependent forces now used more widely</u>

Physical Origin of Density Dependent Force of the Skyrme Type within the Quark Meson Coupling Model

P.A.M. Guichon[1], H.H. Matevosyan[2,3], N. Sandulescu[1,4,5] and A.W. Thomas[2]

	E_B (MeV, exp)	E_B (MeV, QMC)	r_c (fm, exp)	r_c (fm, QMC)
^{16}O	7.976	7.618	2.73	2.702
^{40}Ca	8.551	8.213	3.485	3.415
^{48}Ca	8.666	8.343	3.484	3.468
^{208}Pb	7.867	7.515	5.5	5.42

~ 4%

~ 1%

- **Where analytic form of (e.g. $H_0 + H_3$) piece of energy functional derived from QMC is:**

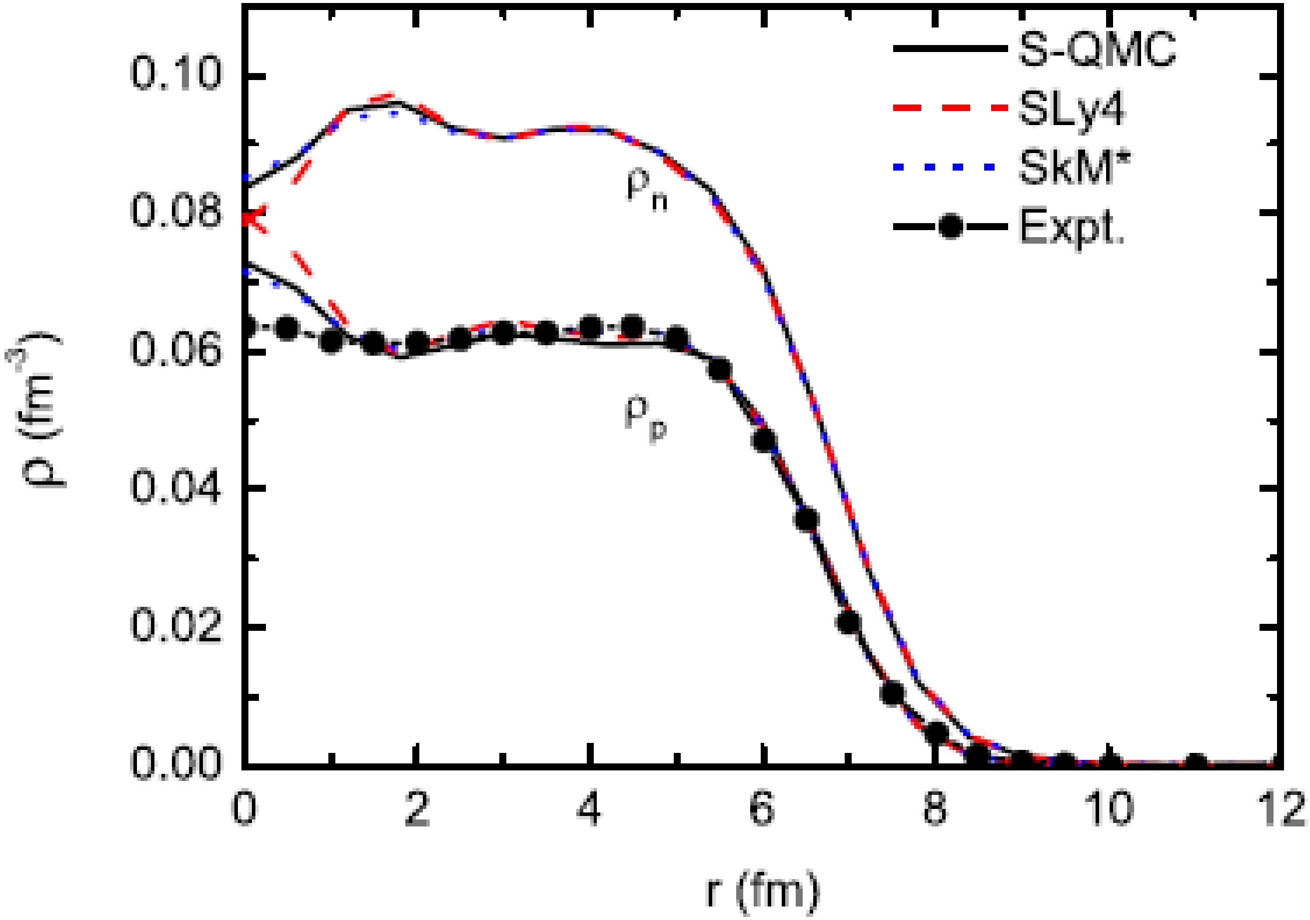
$$\mathcal{H}_0+\mathcal{H}_3 = \rho^2\left[\frac{-3\,G_\rho}{32}+\frac{G_\sigma}{8\,(1+\enclose{circle}{d}\rho\, G_\sigma)^3}-\frac{G_\sigma}{2\,(1+\enclose{circle}{d}\rho\, G_\sigma)}+\frac{3\,G_\omega}{8}\right]+ (\rho_n-\rho_p)^2\left[\frac{5\,G_\rho}{32}+\frac{G_\sigma}{8\,(1+\enclose{circle}{d}\rho\,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

○ highlights

scalar polarizability

Paper II: N P A772 (2006) 1 (nucl-th/0603044)

Nuclear Densities from QMC-Skyrme



Calculation of Furong Xu (2010)

Spin-Orbit Splitting

	Neutrons (Expt)	Neutrons (QMC)	Protons (Expt)	Protons (QMC)
^{16}O $1p_{1/2}$-$1p_{3/2}$	6.10	6.01	6.3	5.9
^{40}Ca $1d_{3/2}$-$1d_{5/2}$	6.15	6.41	6.0	6.2
^{48}Ca $1d_{3/2}$-$1d_{5/2}$	6.05 (Sly4)	5.64	6.06 (Sly4)	5.59
^{208}Pb $2d_{3/2}$-$2d_{5/2}$	2.15 (Sly4)	2.04	1.87 (Sly4)	1.74

Agreement generally very satisfactory – NO parameter adjusted to fit

Shell Structure Away from Stability

- **Use Hartree – Fock – Bogoliubov calculation**

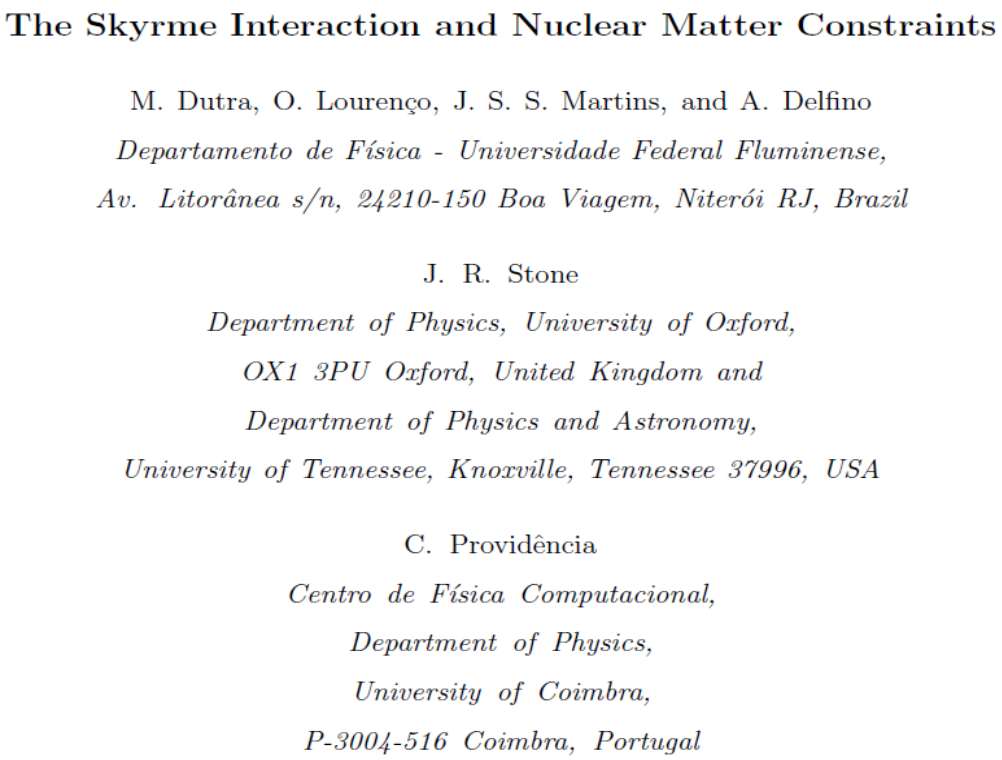
- **Calculated variation of two-neutron removal energy at N = 28 as Z varies from Z = 32 (proton drip-line region) to Z = 18 (neutron drip-line region)**

- **S_{2n} changes by 8 MeV at Z=32**
  S_{2n} changes by 2–3 MeV at Z = 18

- **This strong shell quenching is very similar to Skyrme – HFB calculations of Chabanat et al.,**
  Nucl. Phys. A635 (1998) 231

- **2n drip lines appear at about N = 60 for Ni and N = 82 for Zr**
  (/// to predictions for Sly4 – c.f. Chabanat et al.)

Global search on Skyrme forces



The Skyrme Interaction and Nuclear Matter Constraints

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

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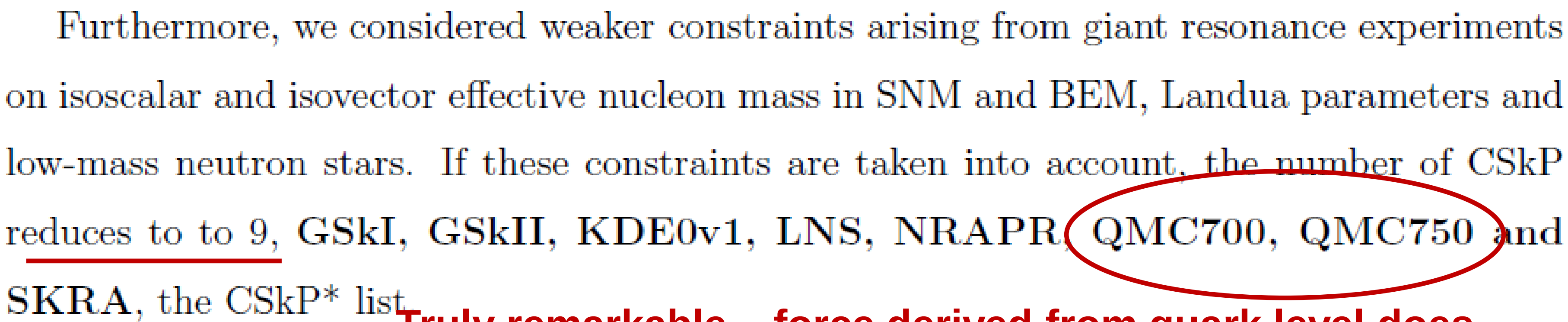
University of Coimbra,
P-3004-516 Coimbra, Portugal

Phys. Rev. C85 (2012) 035201

These authors tested 233 widely used Skyrme 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, Landua 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!

Constraints from Heavy Ion Reactions

– from Dutra et al. (2010)

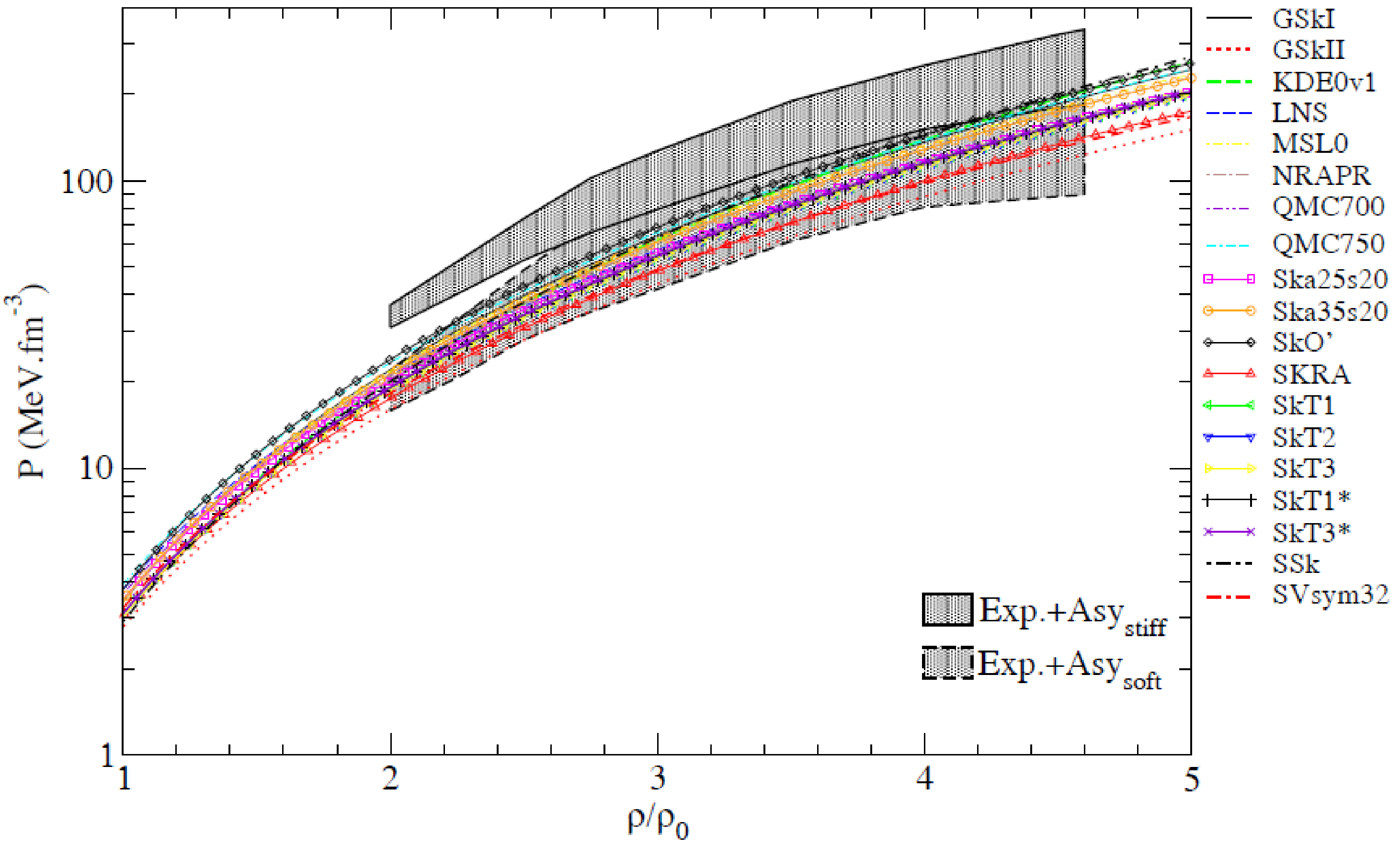


FIG. 4: (color online). Constraint **PNM2**: Pressure in the pure neutron matter as a function of density in the region 2 ¡ $\frac{\rho}{\rho_o}$ ¡ 4.6. For detailed explanation see Ref. [24].

[24] Danielewicz, Nucl Phys A727 (2003) 233

More on derived Skyrme force later

- **Last part of the talk will deal with recent unpublished studies of the derived Skyrme force, with it’s unusual density dependence**

- **Across the entire periodic table**

Mesons in Nuclei

- **At Hartree level mesons like ω, η and η’ contain light quark-anti-quark pairs**

- **Repulsive vector potential cancels for q and $\bar{q}$**
  (s and $\bar{s}$ do not couple to σ, ω and ρ)

- **Thus they must feel attraction associated with the mean scalar field** **(Saito et al., Phys.Rev. C55 (1997) 2637-2648)**

- **Initial estimates significantly underestimated absorption of the ω, which adds repulsion**

  - **but V. Metag finds hint of mild attraction in C : -20 ± 25 ± 10 MeV**

η’ in Nuclei

(Bass, Jido, Hirenzaki, Lu, Nagahiro, Saito, Tsushima....)

- **Complicated/made more interesting by axial anomaly**

$$
\begin{aligned}
m^2_{\eta',\eta} &= (m_{\mathrm{K}}^2 + \tilde{m}^2_{\eta_0}/2) \\
&\pm \frac{1}{2}\sqrt{(2m_{\mathrm{K}}^2 - 2m_\pi^2 - \frac{1}{3}\tilde{m}^2_{\eta_0})^2 + \frac{8}{9}\tilde{m}^4_{\eta_0}}
\end{aligned}
$$

- **But absorption significantly less than the ω**

  (Kotulla et al., Phys. Rev. Lett. 100 (2008) 192302)

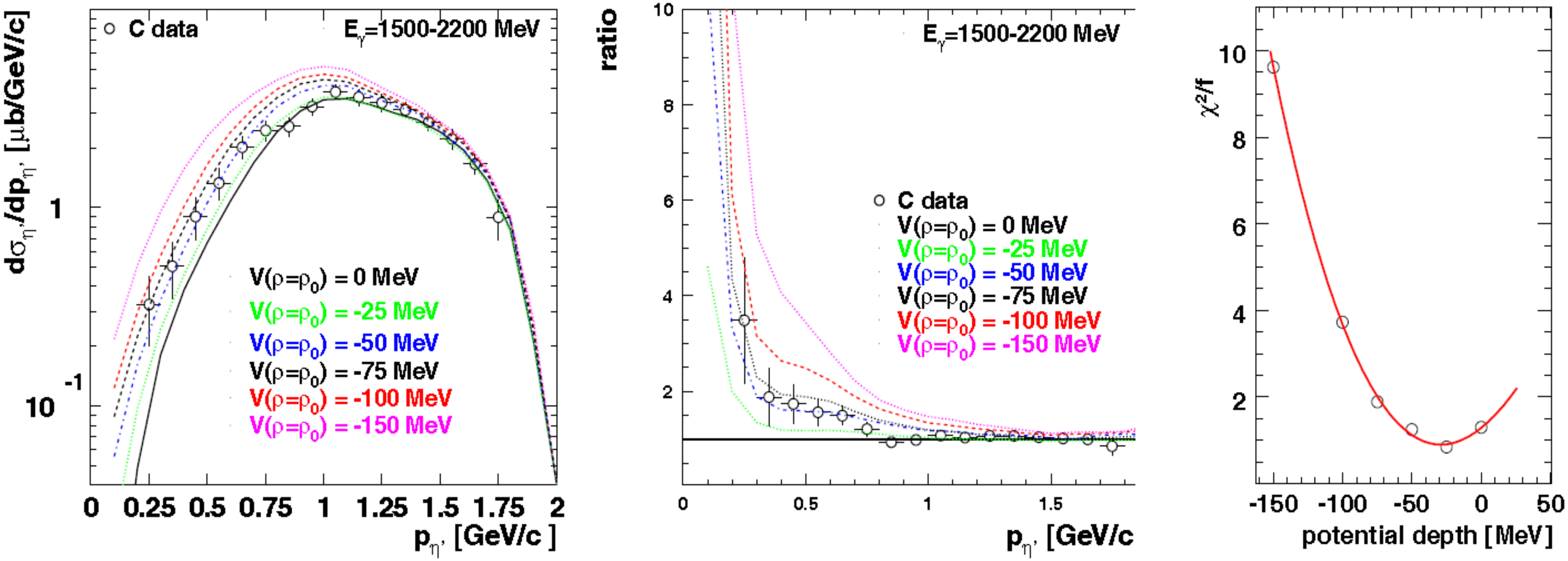
- **M. Nanova (arXiv:1311.0122) finds that the η’ feels attraction of -37 ± 10 ± 10 MeV in ^{12}C**

- **This is very similar to Bass and Thomas (Acta Phys Pol B41 (2010) 2239)**

	m (MeV)	m^* (MeV)	Re a (fm)
η_8	547.75	500.0	0.43
η (-10^o)	547.75	474.7	0.64
η (-20^o)	547.75	449.3	0.85
η_0	958	878.6	0.99
η' (-10^o)	958	899.2	0.74
η' (-20^o)	958	921.3	0.47

η’ in Nuclei

Nanova arXiv:1311.0122 :
η’ feels attraction of -37 ± 10 ± 10 MeV in ^{12}C



- **This, plus weak absorption, suggests a search for η’ bound states is very worthwhile!**

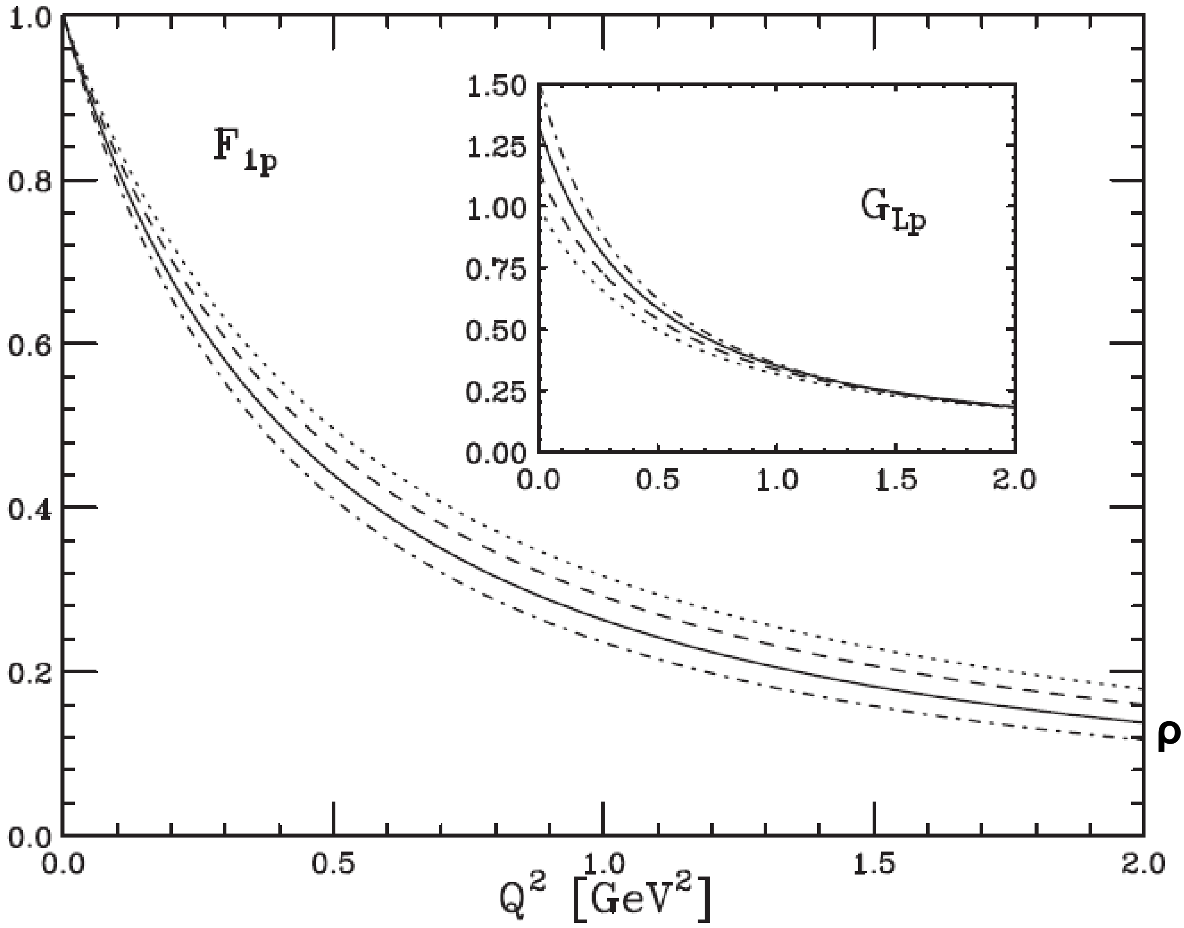
- **Note that search for bound charmed mesons also attractive – QMC predicts D^- bound in Pb by 10-30 MeV**

(Saito et al., Phys. Rev. C59 (1999) 2824-2828)

Modified Electromagnetic Form Factors In-Medium

NJL Model

(scalar di-quarks only)

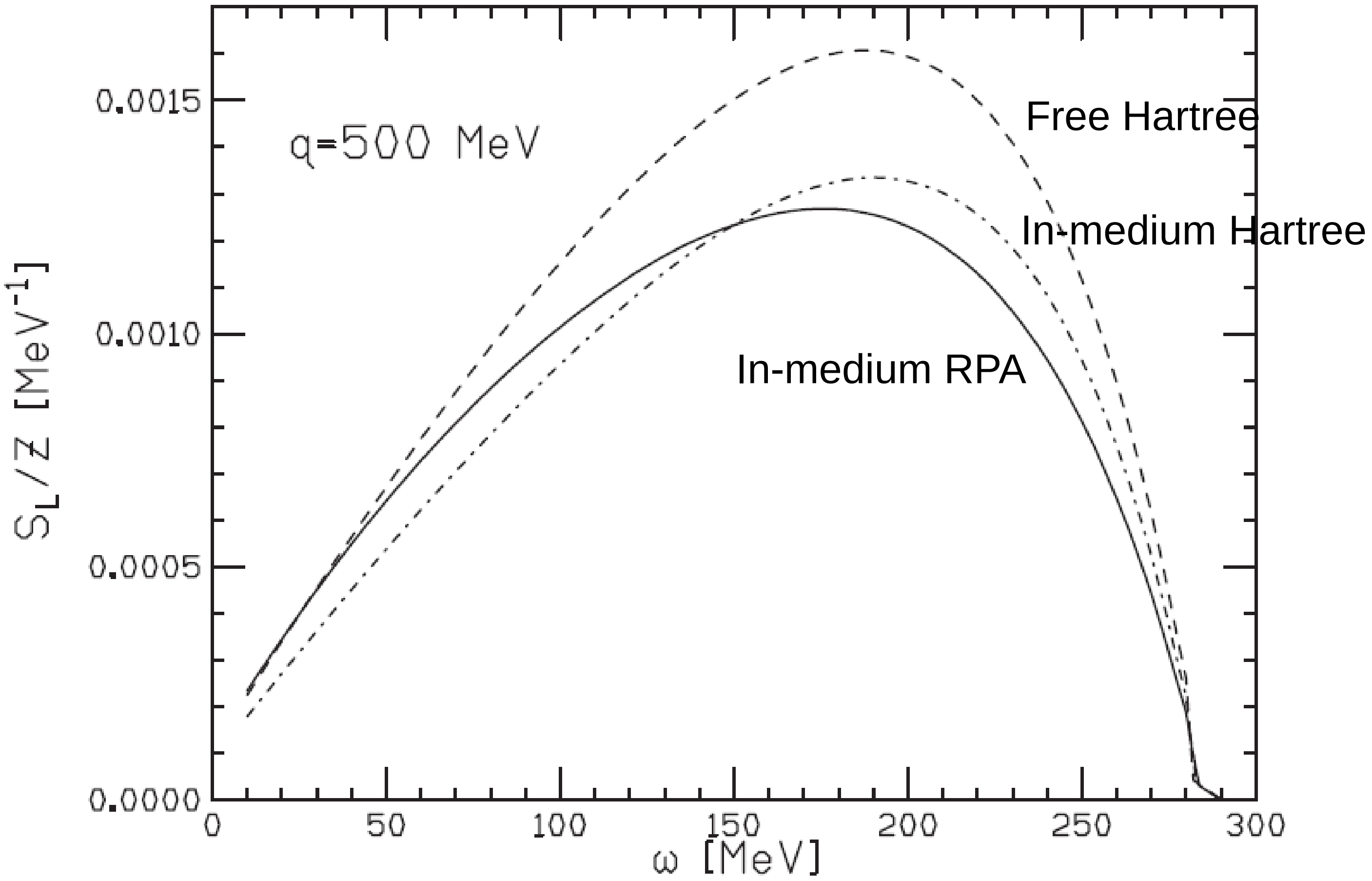


ρ=0, 0.5, 1.0 and 1.5ρ_0

Horikawa and Bentz, nucl-th/0506021

Longitudinal response function

(New results from JLab, Meziani et al., eagerly awaited)

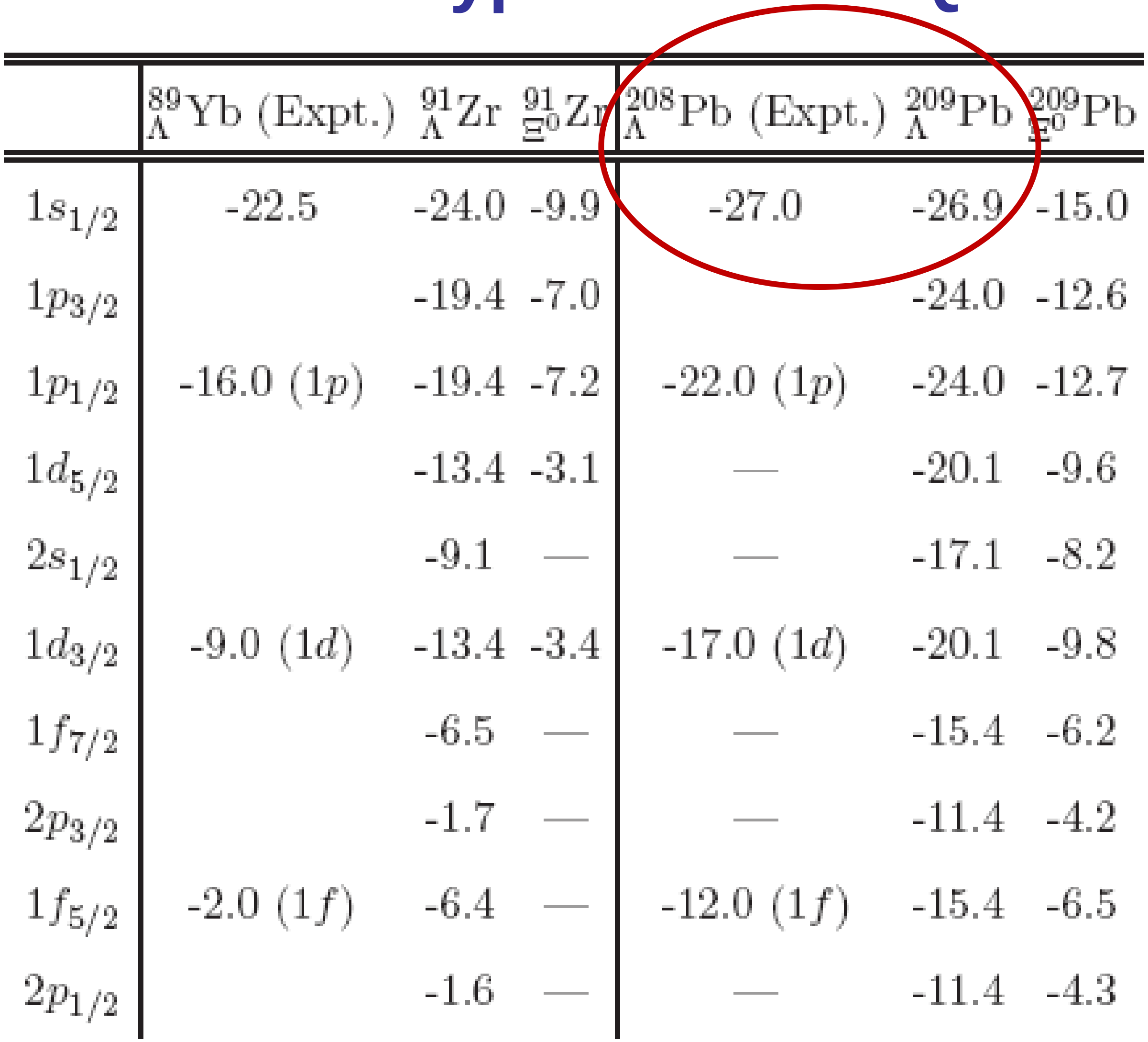


Horikawa and Bentz, nucl-th/0506021

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

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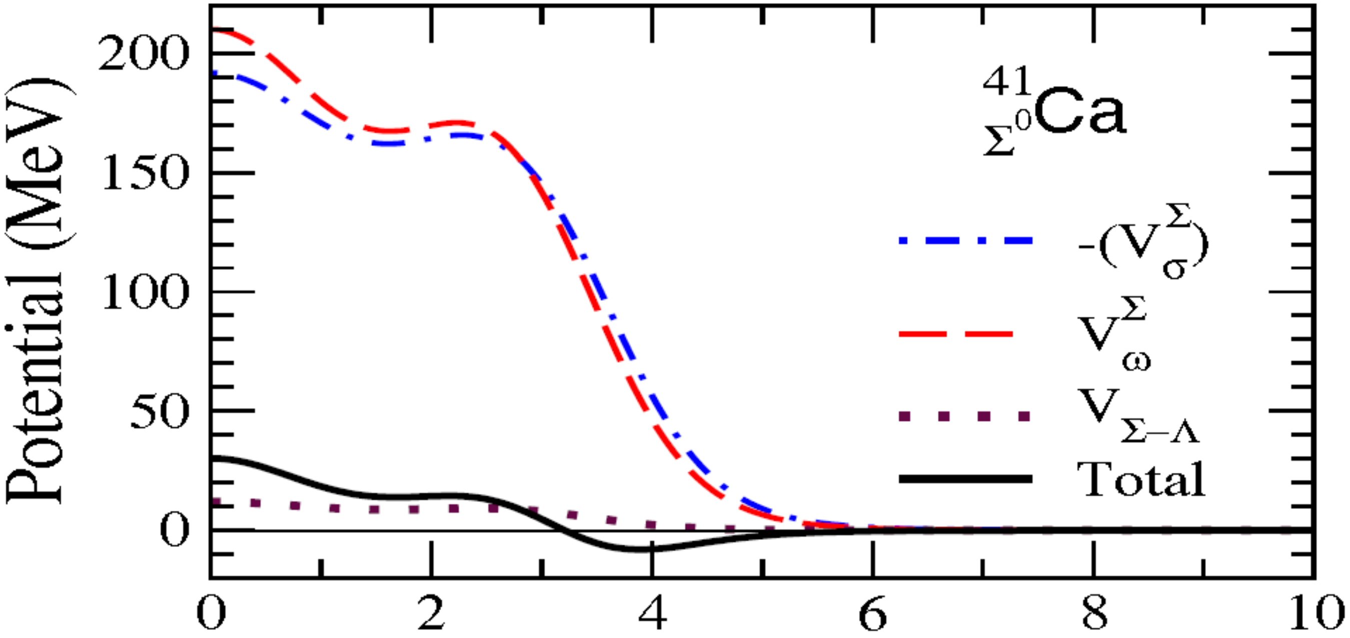
Σ – hypernuclei

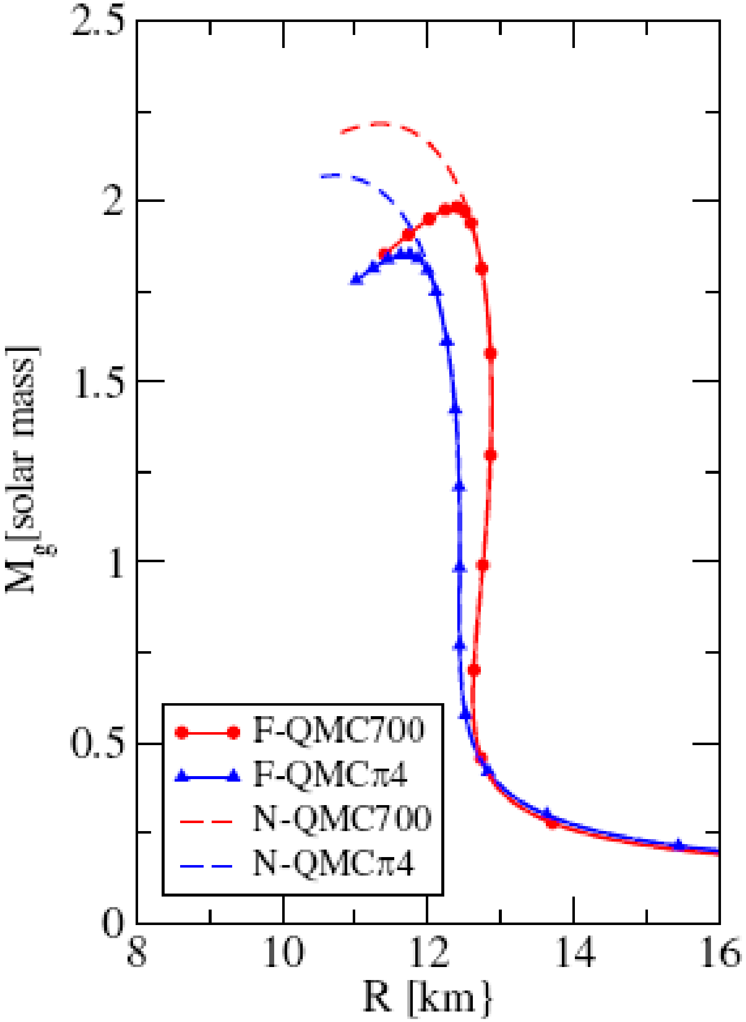
Σ-hypernuclei unbound :
because of increase of hyperfine interaction with density

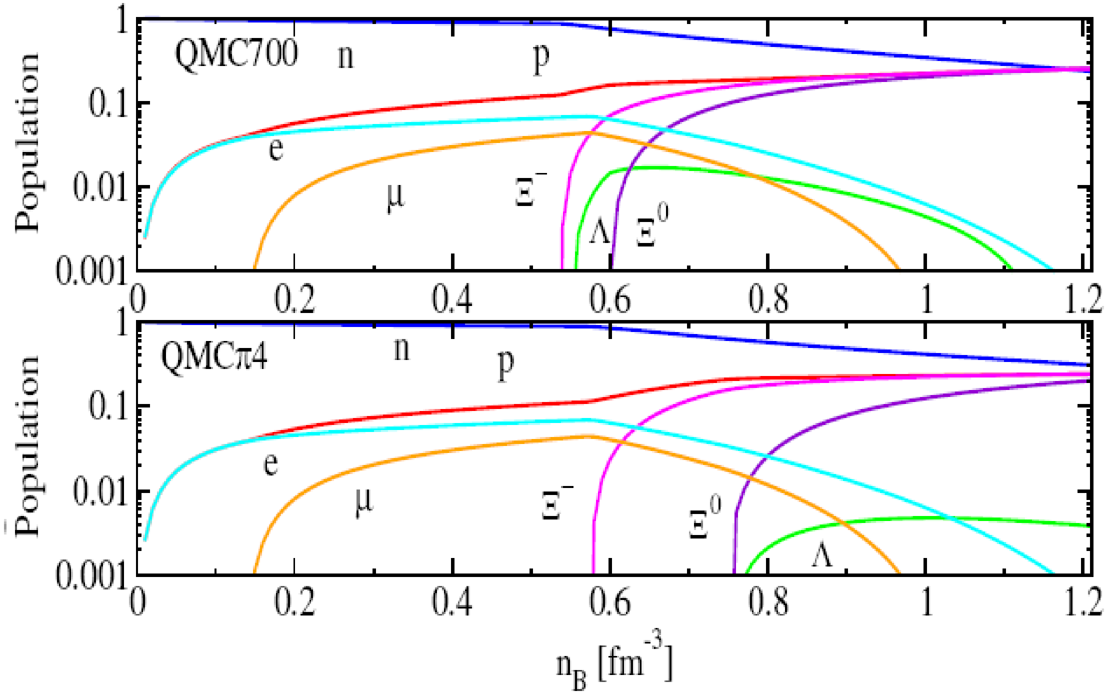
– e.g. for Σ^0 in ^{40}Ca:
central potential +30 MeV and few MeV attraction
in surface (-10MeV at 4fm)



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

Consequences for Neutron Star





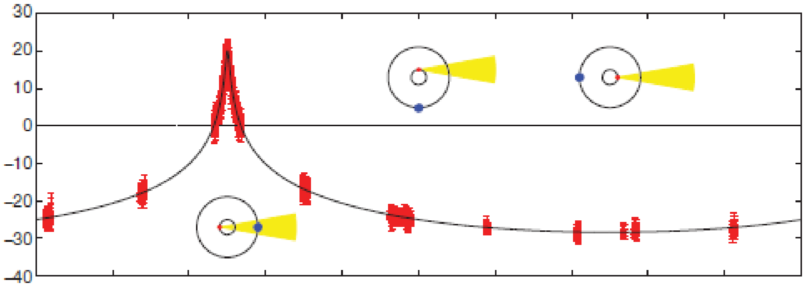
Rikovska-Stone et al., NP A792 (2007) 341

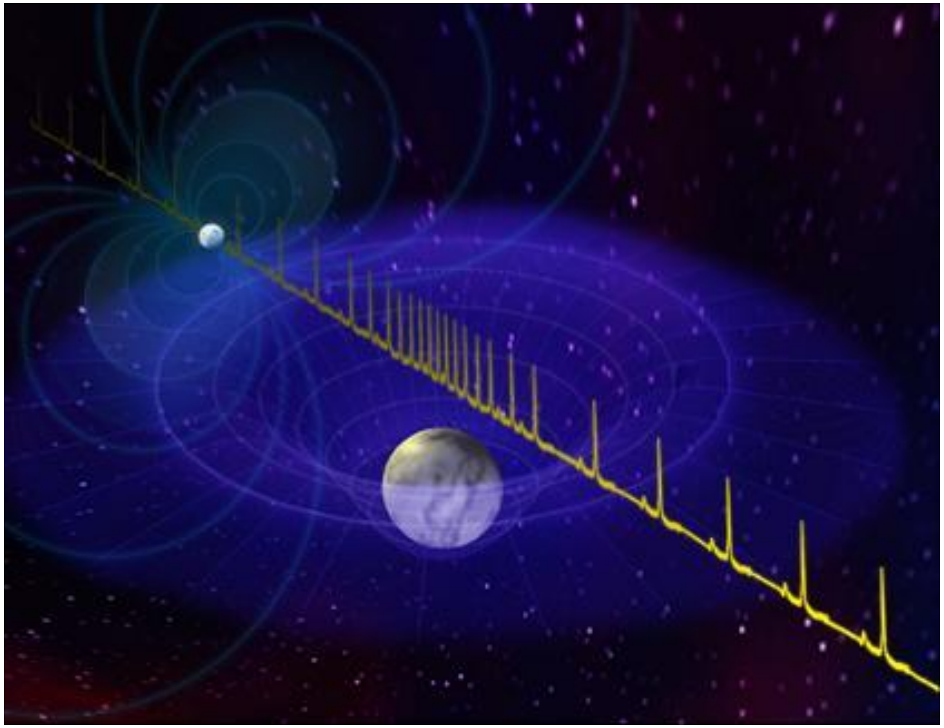
LETTER

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 published work!)

J1614-2230

Most Recent Development

(Whittenbury, Carroll, Stone & Tsushima)

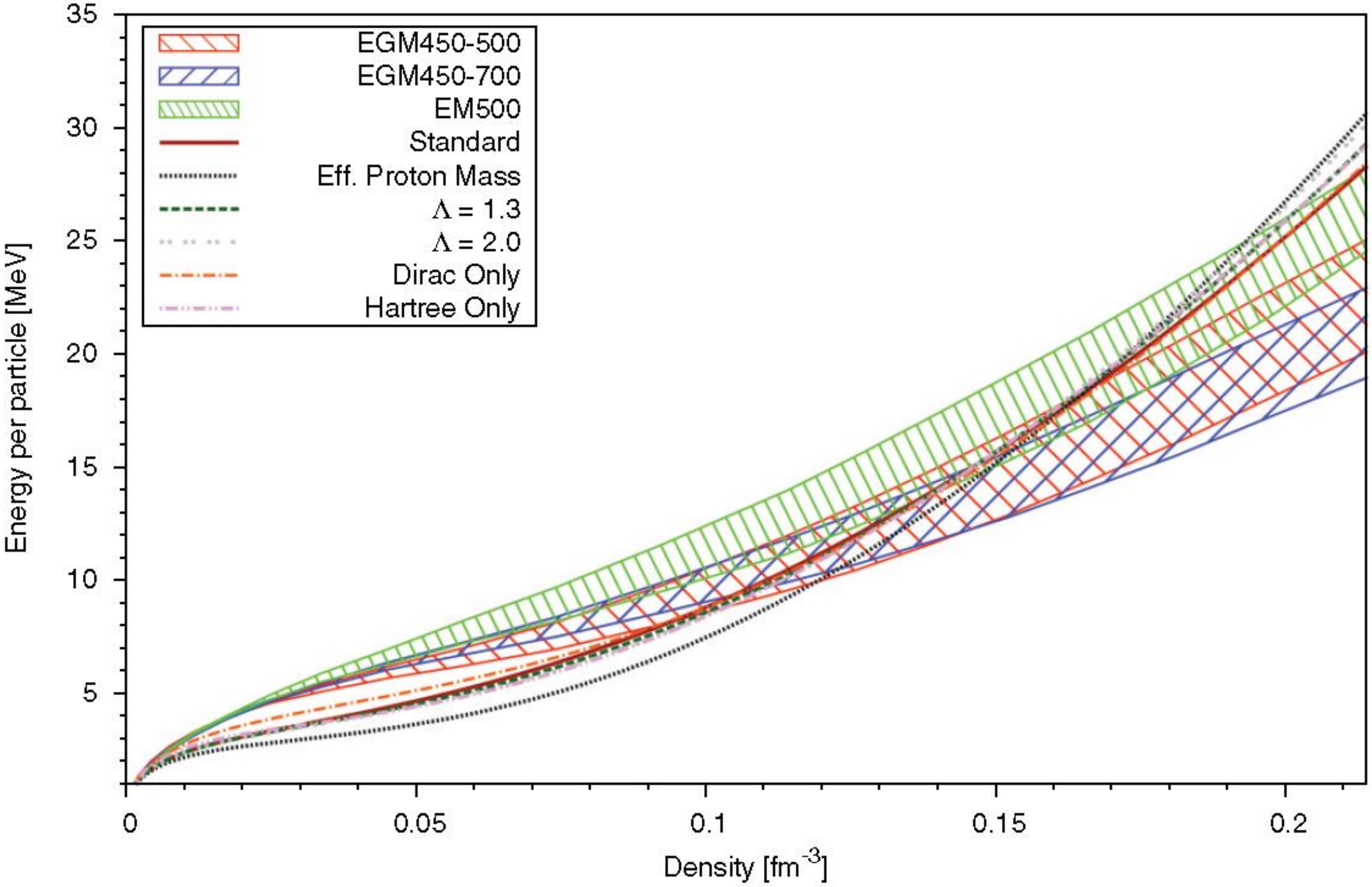
- **Include in Fock terms the effect of the Pauli coupling (i.e. $F_2 \sigma^{\mu\lambda} q_\lambda$ term) in ρ and ω exchanges between all baryons**

- **This introduces more parameters**
  - **because of short-distance suppression of relative wave function and possible form factors**

- **In line with recent work of Stone, Stone and Moszkowski , require compressibility at ρ_0 in the range 250-330 MeV**

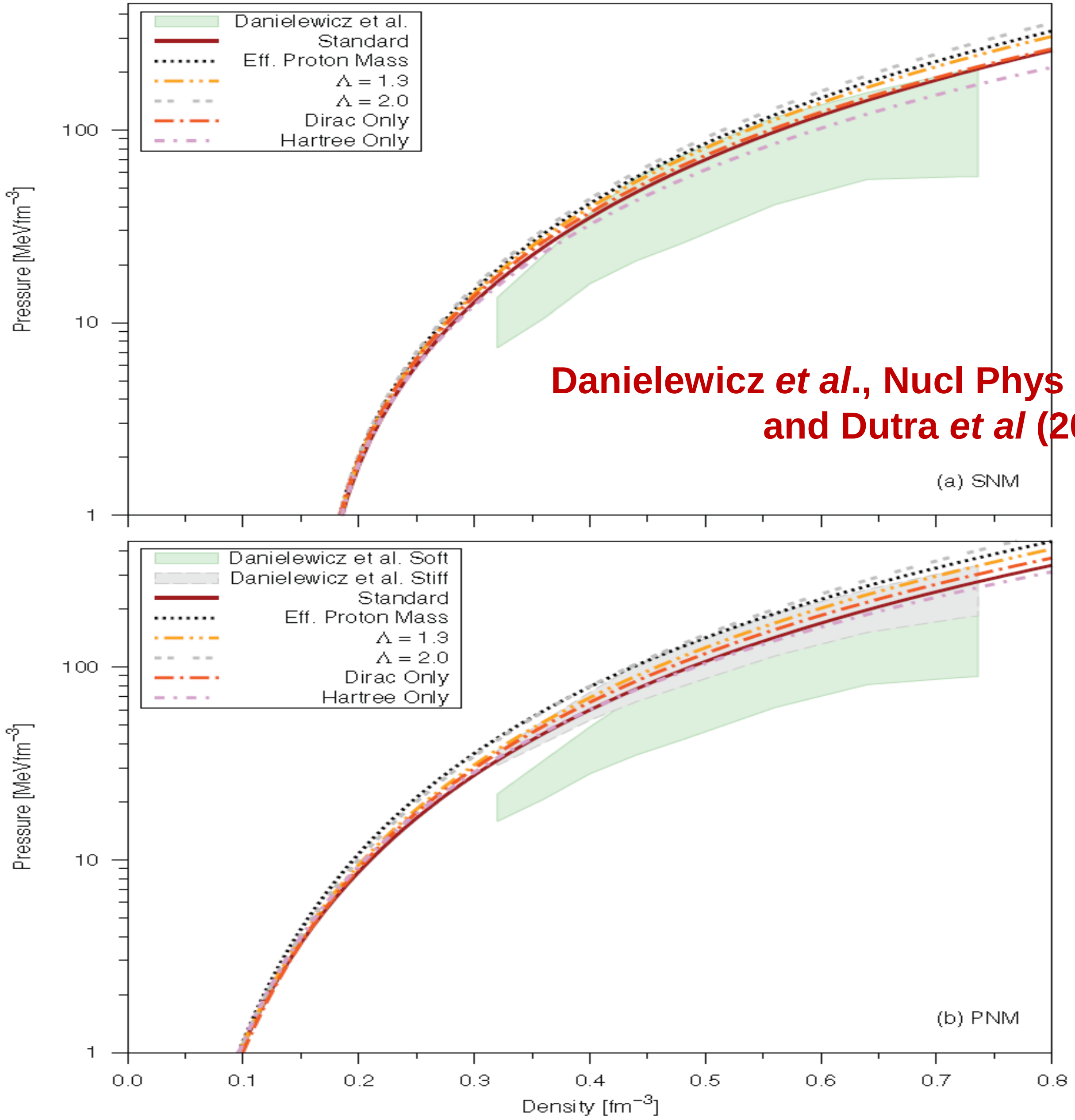
see : Whittenbury *et al*., arXiv:1307.4166 (PRC 89 (2014) 065801)
(related work: Miyatsu *et al*., Phys.Lett. B709 (2012) 242
and Long *et al*., Phys. Rev. C85 (2012) 025806)

Pure Neutron Matter (PNM) c.f. EFT



Whittenbury *et al*., PRC 89 (2014) 065801 - Details EFT Tews et al., PRL 110 (2103) 032504

Heavy Ion Constraints



Danielewicz *et al*., Nucl Phys A727 (2003) 233
and Dutra *et al* (2010)

Equation of State

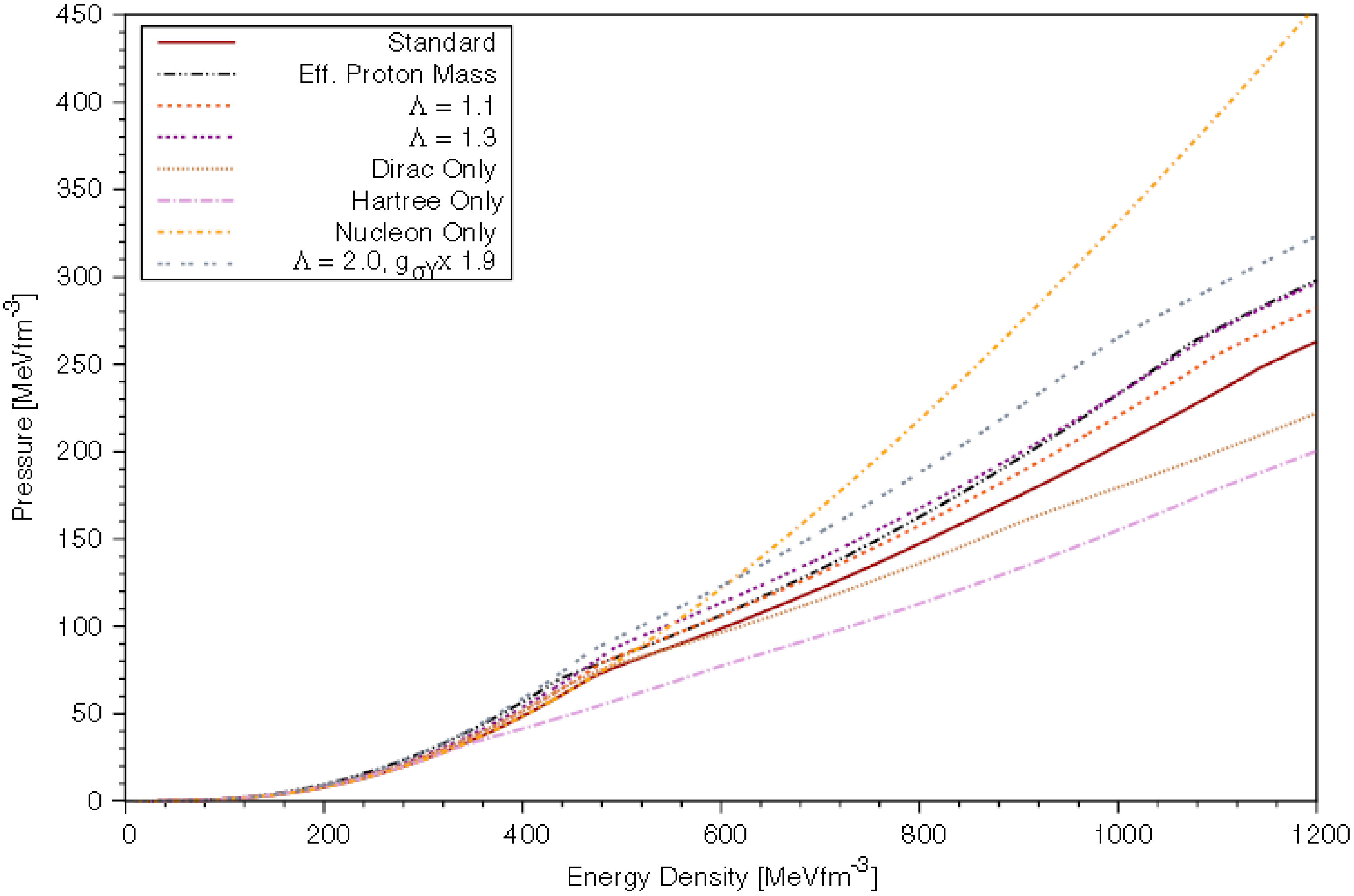
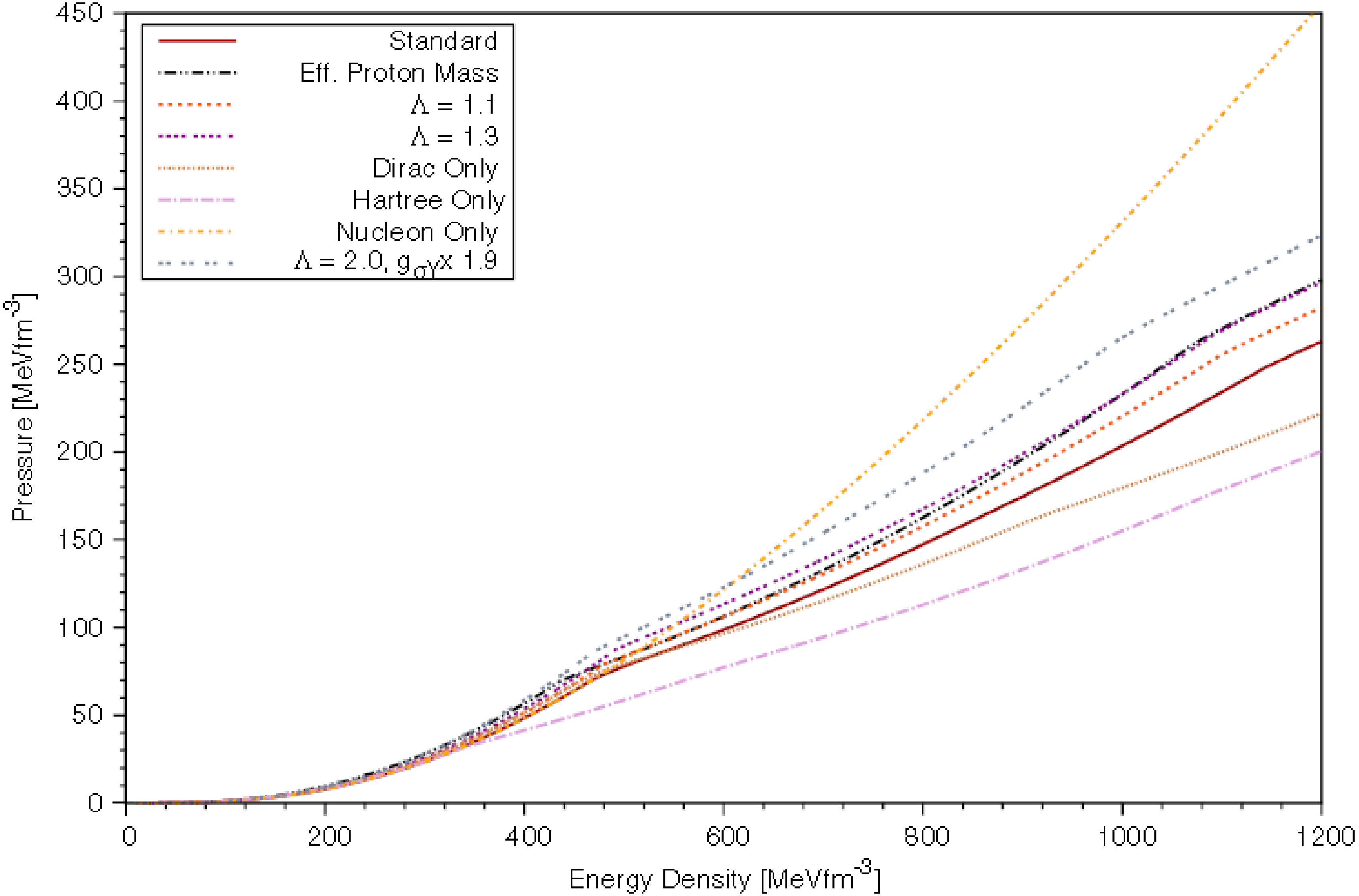


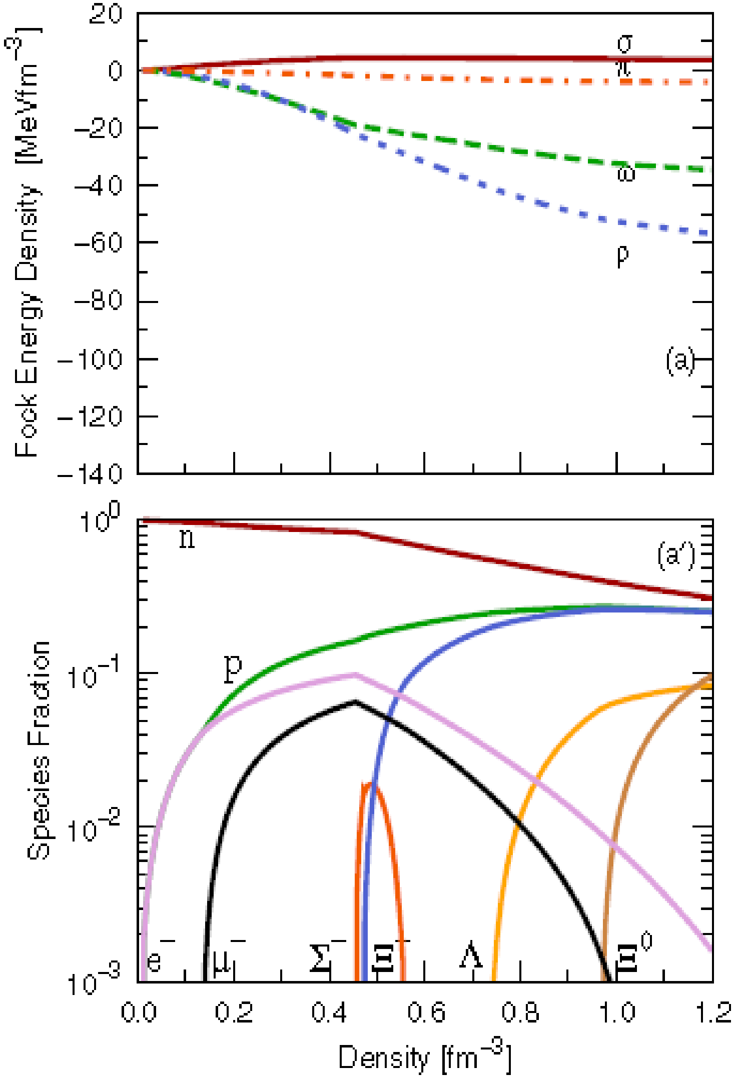
TABLE II. Couplings, nuclear matter properties, selected hyperon optical potentials, and neutron star properties determined for our standard case (for which $\Lambda = 0.9$ GeV, and $R_N^{\rm free} = 1.0$ fm) and the effect of subsequent variations in which differences from the standard parameter set are indicated in column 1. The tabulated quantities at saturation are the slope and curvature of the symmetry energy, L_0 and $K_{\rm sym}$, the incompressibility K_0, skewness coefficient Q_0, calculated at saturation density, and volume component of isospin incompressibility $K_{\tau,v}$, respectively. Tabulated neutron star quantities are the stellar radius, maximum stellar mass, and corresponding central density (units $\rho_0 = 0.16$ fm^{-3}).

Model/ scenario	$g_{\sigma N}$	$g_{\omega N}$	g_ρ	K_0 (MeV)	L_0 (MeV)	$K_{\rm sym}$ (MeV)	Q_0 (MeV)	$K_{\tau,v}$ (MeV)	U_Λ (MeV)	U_{Σ^-} (MeV)	U_{Ξ^-} (MeV)	$M_{\rm max}$ ($M_\odot$)	R (km)	$\rho_c^{\rm max}$ (ρ_0)
Standard	8.97	9.38	4.96	273	84	−23	−305	−431	3	25	5	1.80	11.80	5.88
$\Lambda = 1.0$	9.07	9.73	5.05	278	85	−15	−282	−439	10	32	8	1.84	11.86	5.82
$\Lambda = 1.1$	9.16	10.06	5.16	283	86	−8	−261	−446	16	39	11	1.88	11.94	5.70
$\Lambda = 1.2$	9.24	10.37	5.28	286	87	−2	−241	−451	23	46	15	1.92	12.03	5.60
$\Lambda = 1.3$	9.31	10.67	5.40	289	88	4	−224	−456	29	53	18	1.95	12.10	5.52
$\Lambda = 1.1, g_{\sigma Y} \times 1.3$	9.16	10.06	5.16	283	86	−8	−261	−446	−15	14	−4	1.84	11.91	5.78
$\Lambda = 1.3, g_{\sigma Y} \times 1.3$	9.31	10.67	5.40	289	88	4	−224	−456	−3	28	3	1.92	12.01	5.66
$\Lambda = 2.0, g_{\sigma Y} \times 1.9$	9.69	12.27	6.16	302	92	31	−137	−478	−29	20	−7	2.07	12.24	5.38
Increased $f_{\rho N}/g_{\rho N}$	8.70	9.27	3.86	267	81	−34	−321	−424	6	27	6	1.77	11.61	6.14
Fock $\delta\sigma$	9.01	9.44	4.97	273	84	−21	−296	−432	4	26	5	1.81	11.82	5.86
Eff. Proton Mass	10.40	11.0	4.55	297	101	64	−190	−476	11	41	10	1.94	12.20	5.48
Eff. Proton Mass, $\Lambda = 1.1$	11.08	12.31	4.85	311	111	126	−87	−509	34	67	22	2.07	12.57	5.08
Eff. Proton Mass + $\delta\sigma$	10.89	11.55	4.53	285	109	132	−232	−432	17	49	13	1.99	12.22	5.46
Dirac Only	10.10	9.22	7.84	294	85	0	−299	−424	−23	4	−8	1.79	12.33	5.22
Hartree Only	10.25	7.95	8.40	283	88	−17	−455	−405	−49	−23	−21	1.54	11.73	6.04
Nucleon Only	8.97	9.38	4.96	273	84	−23	−305	−431	3	25	5	2.10	11.08	6.46
$R = 0.8$	9.30	9.85	4.98	277	85	−15	−269	−443	6	25	5	1.83	11.88	5.80
App. $S_0 = 32.5$	9.05	9.38	4.86	275	82	−27	−303	−429	2	24	4	1.80	11.82	5.82
App. $S_0 = 30.0$	9.31	9.35	4.50	280	74	−24	−298	−391	−4	19	1	1.81	11.82	5.76
$S_0 = 30.0$	9.24	9.36	4.61	278	76	−20	−299	−394	−2	21	2	1.81	11.81	5.80

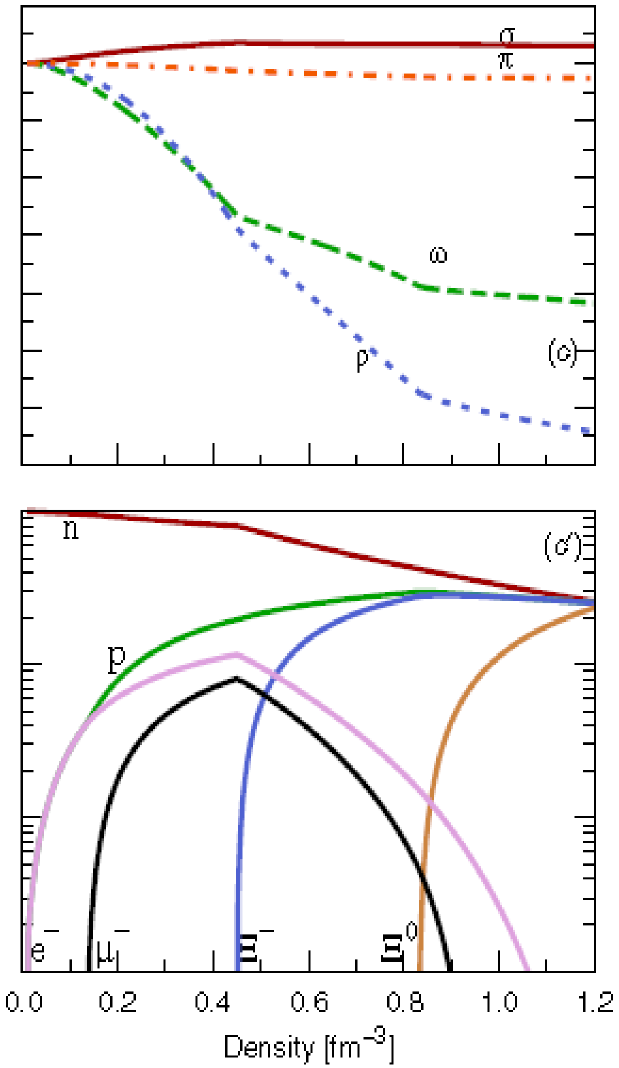
Equation of State



Particle content



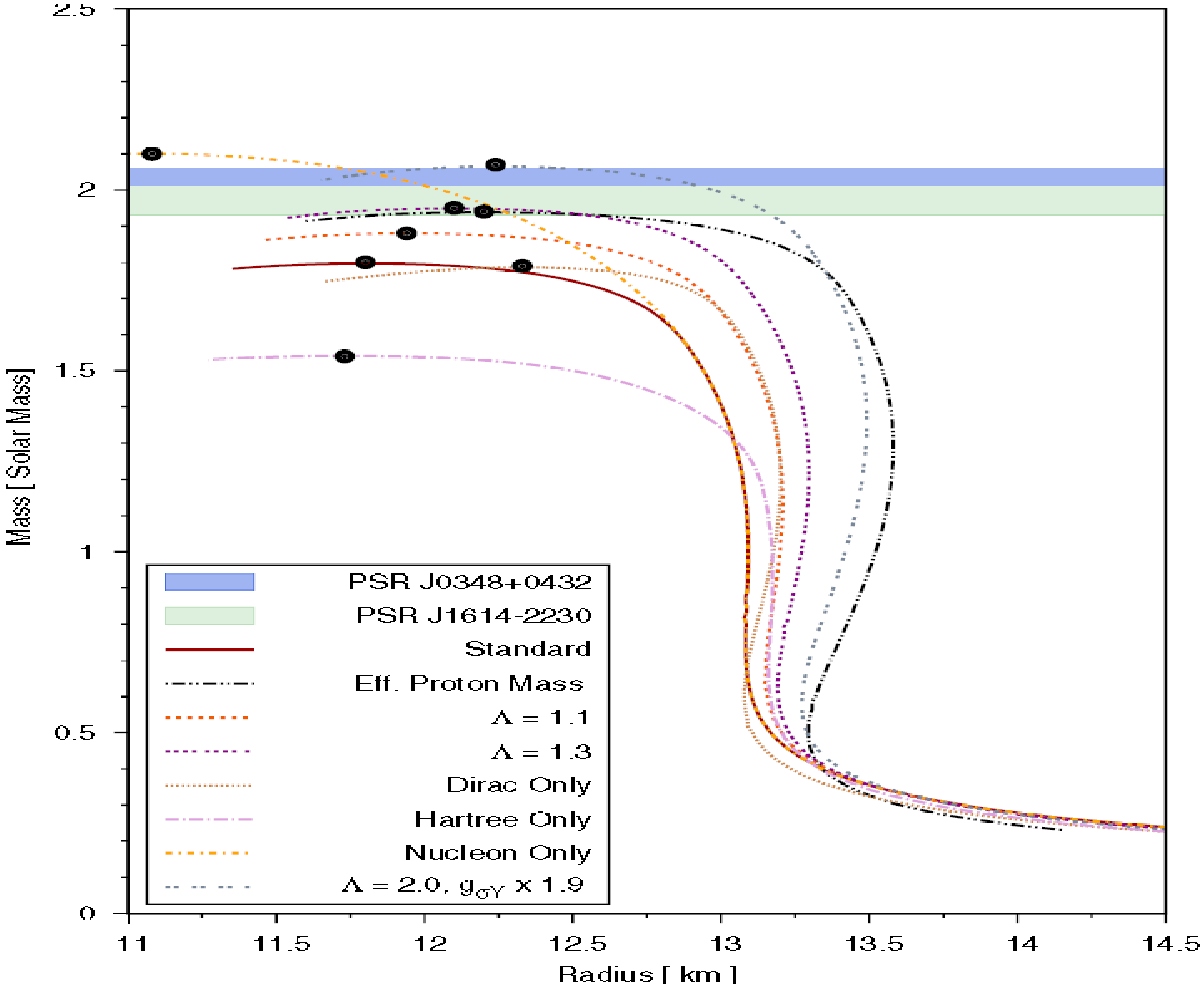
Standard



Hypernuclei corrected

Whittenbury *et al*., PRC 89 (2014) 065801

Mass vs Radius



Whittenbury *et al*., PRC 89 (2014) 065801

New work:

Systematic approach to finite nuclei

(This work is *in preparation* for publication: collaborators are P.A.M. Guichon, P. G. Reinhard and J. R. Stone)

- Allow 3 basic quark-meson couplings to vary so that nuclear matter properties reproduced within errors

$-17 < E/A < -15$ MeV

$0.15 < \rho_0 < 0.17$ fm^{-3}

$28 < J < 34$ MeV

$L > 25$ MeV

$250 < K_0 < 350$ MeV

- Fix at overall best fit for binding energies of finite nuclei

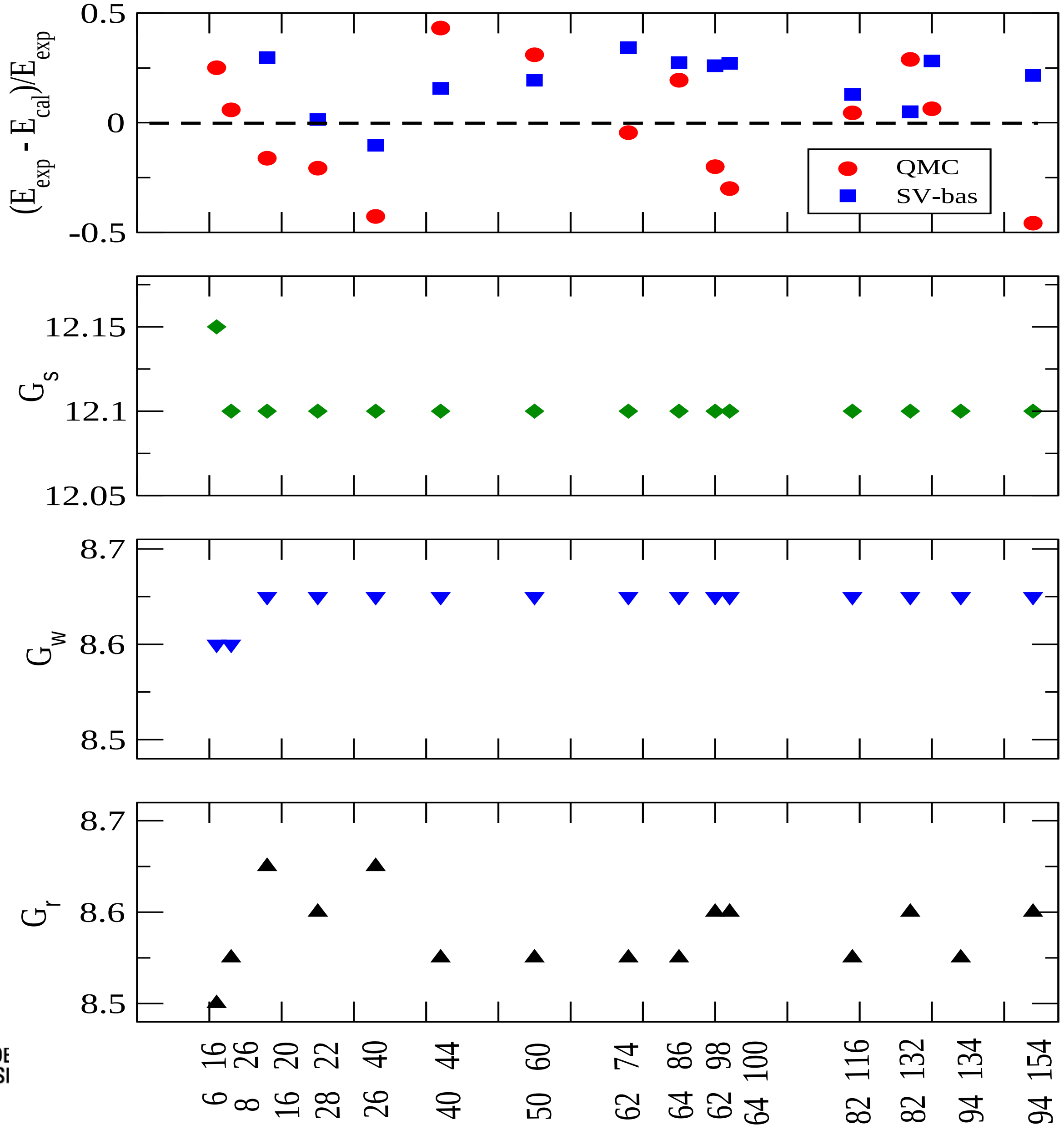
Overview of Nuclei Studied – Across Periodic Table

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 more challenging cases of p- or n-rich nuclei

Overall agreement better than 0.5%



c.f. SV-bas
14 parameters
fit to wide of
binding
(100 nuclei),
charge radii
etc.

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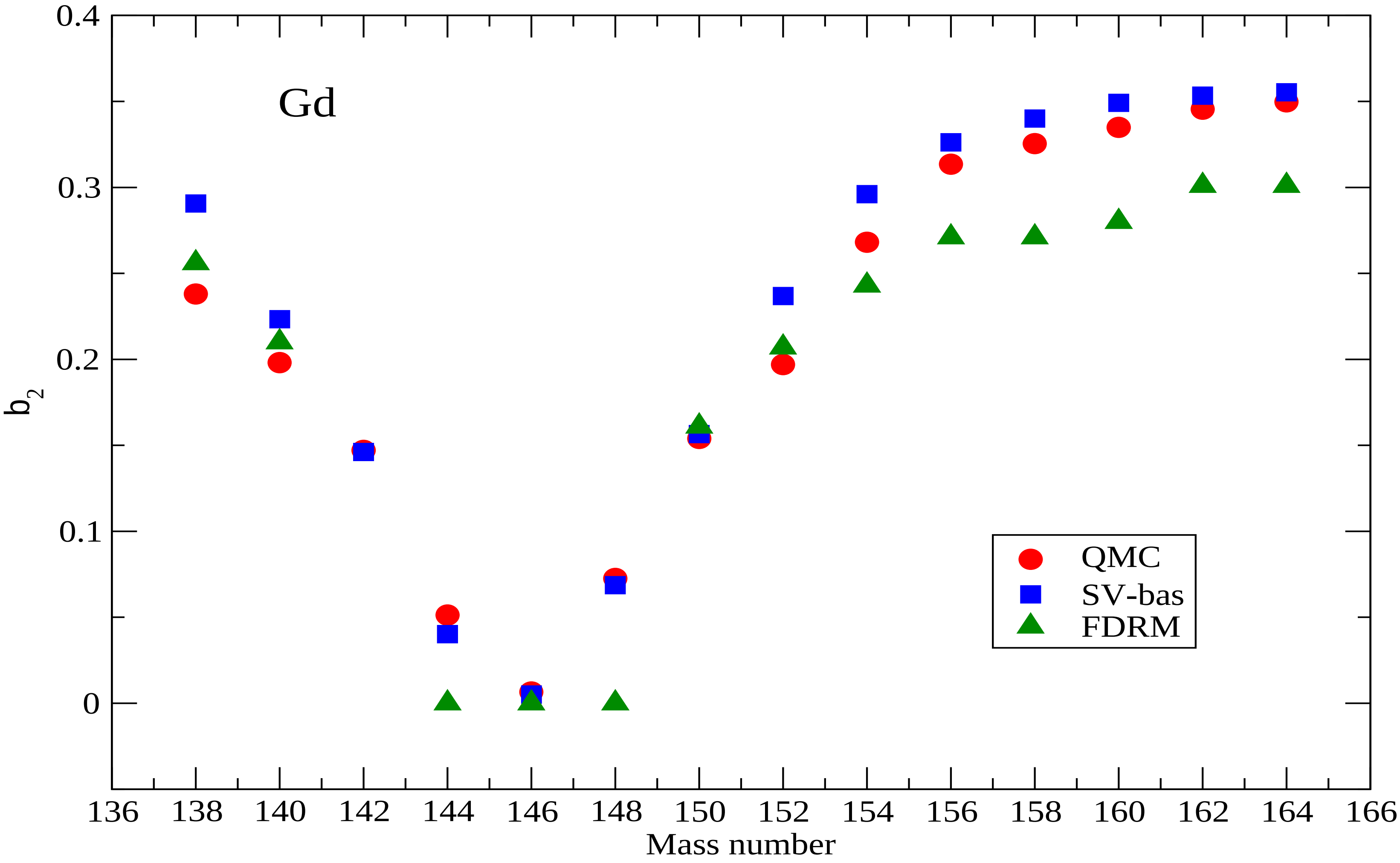
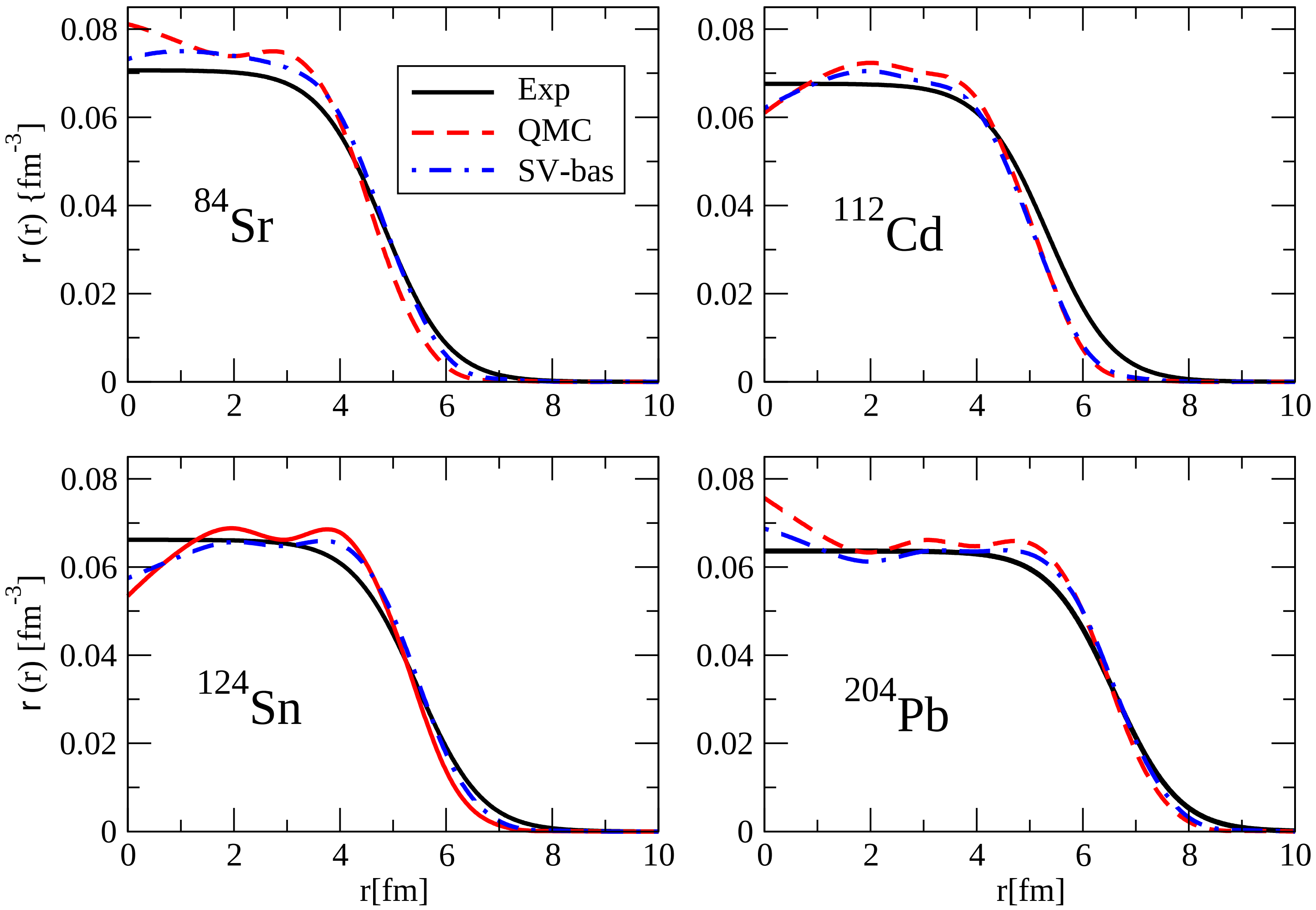
Even Gd isotopes

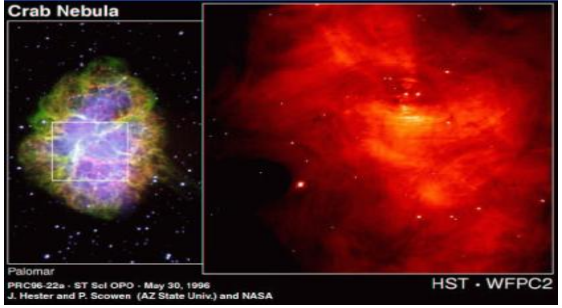


SV-bas: P. Klupfel et al., Phys. Rev. C 79, 034310 (2009)
FDRM: P. Moller et al., ADNDT, 59, 185 (1995)

Charge Distributions



Summary



- Relativity is essential

- Intermediate attraction in NN force is STRONG 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

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Summary$_2$

- Same model also yields realistic, density dependent Λ N, Σ N, Ξ N forces (not yet published)
  − with NO additional parameters

- Availability of realistic, density dependent H N and H H forces is essential for $\rho > 3\,\rho_0$

- Already important results for n stars : mass as large as 2.1 solar masses possible with hyperons

- Inclusion of Pauli terms in Fock calculation presents new challenges: Λ hypernuclei no longer bound

- Can modify couplings to bind Λ hypernuclei and still get massive n-stars – but many open questions
  - not least, transition to quark matter?

Summary$_3$

- Initial systematic study of finite nuclei very promising
    - remember just 3 parameters fixed by nuclear matter
- Super-heavies (Z > 100) especially good (typically better than 0.25%)!
- Binding energies typically within 0.5% or better across the periodic table
- Deformation, spin-orbit splitting and charge distributions all look good (NOT fit – only binding)

Special Mentions……

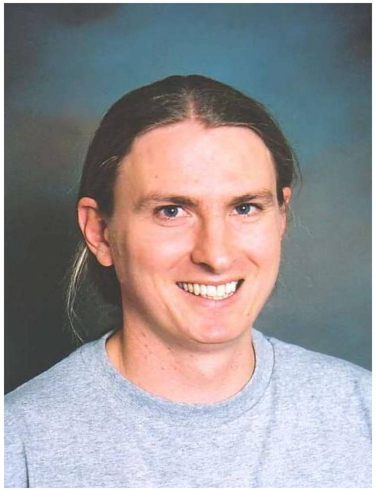
Guichon

Whittenbury

Stone

Tsushima

Bentz



Cloët

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

September 11-16 2016

exceptional!

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STRUCTURE OF 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**

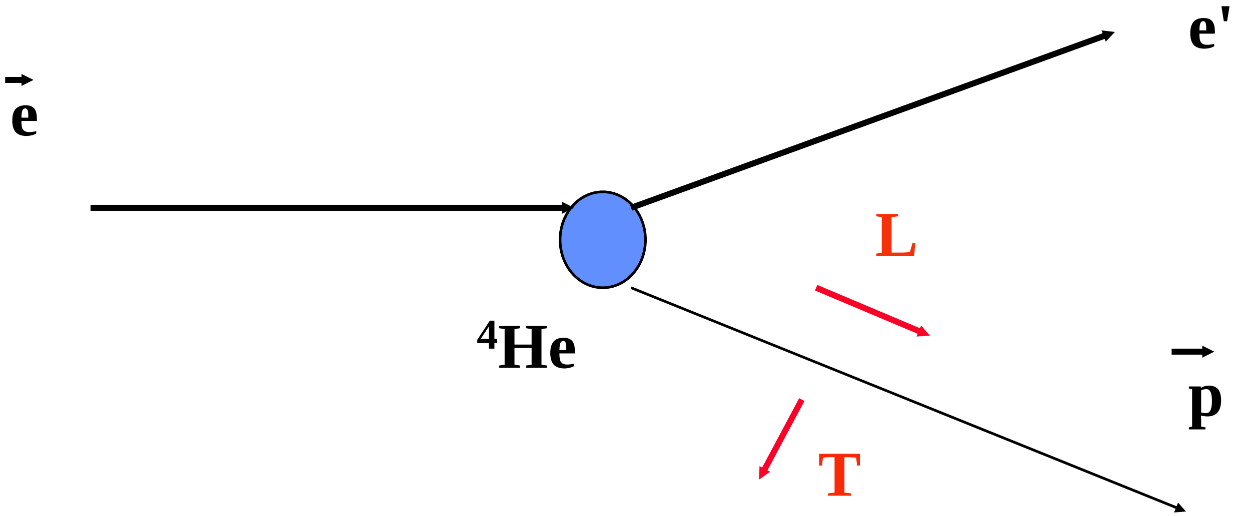
Most recent nuclear structure results

- **Results obtained using SKYAX code of P. G. Reinhard**

- **2 BCS pairing parameters (density dependent, contact pairing force) fitted from pairing gaps in Sn isotopes**

Experimental Test of QMC at Mainz & JLab*

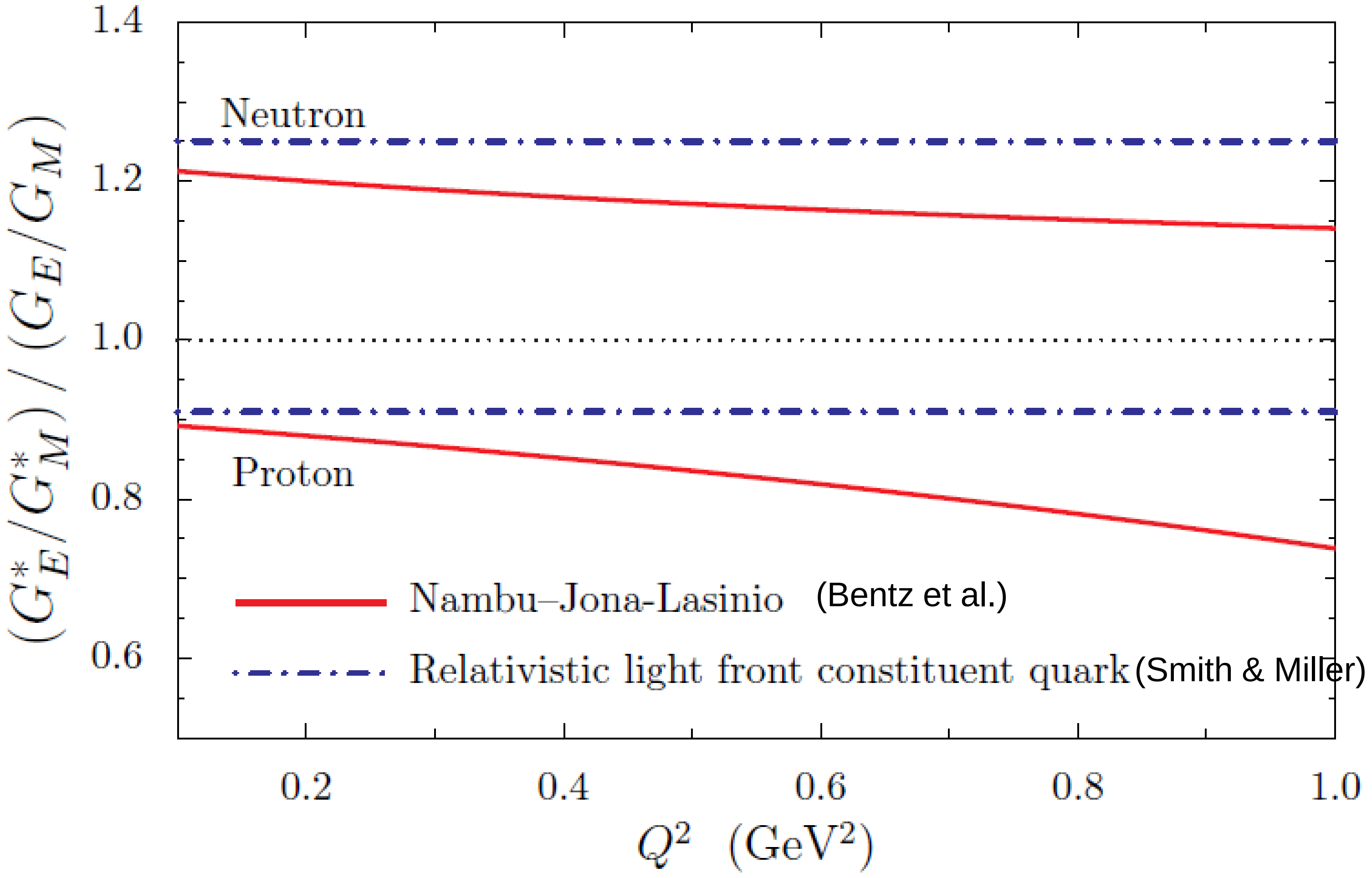
Capacity to measure polarization in coincidence:



$\sigma_T / \sigma_L \sim G_E/G_M$: 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

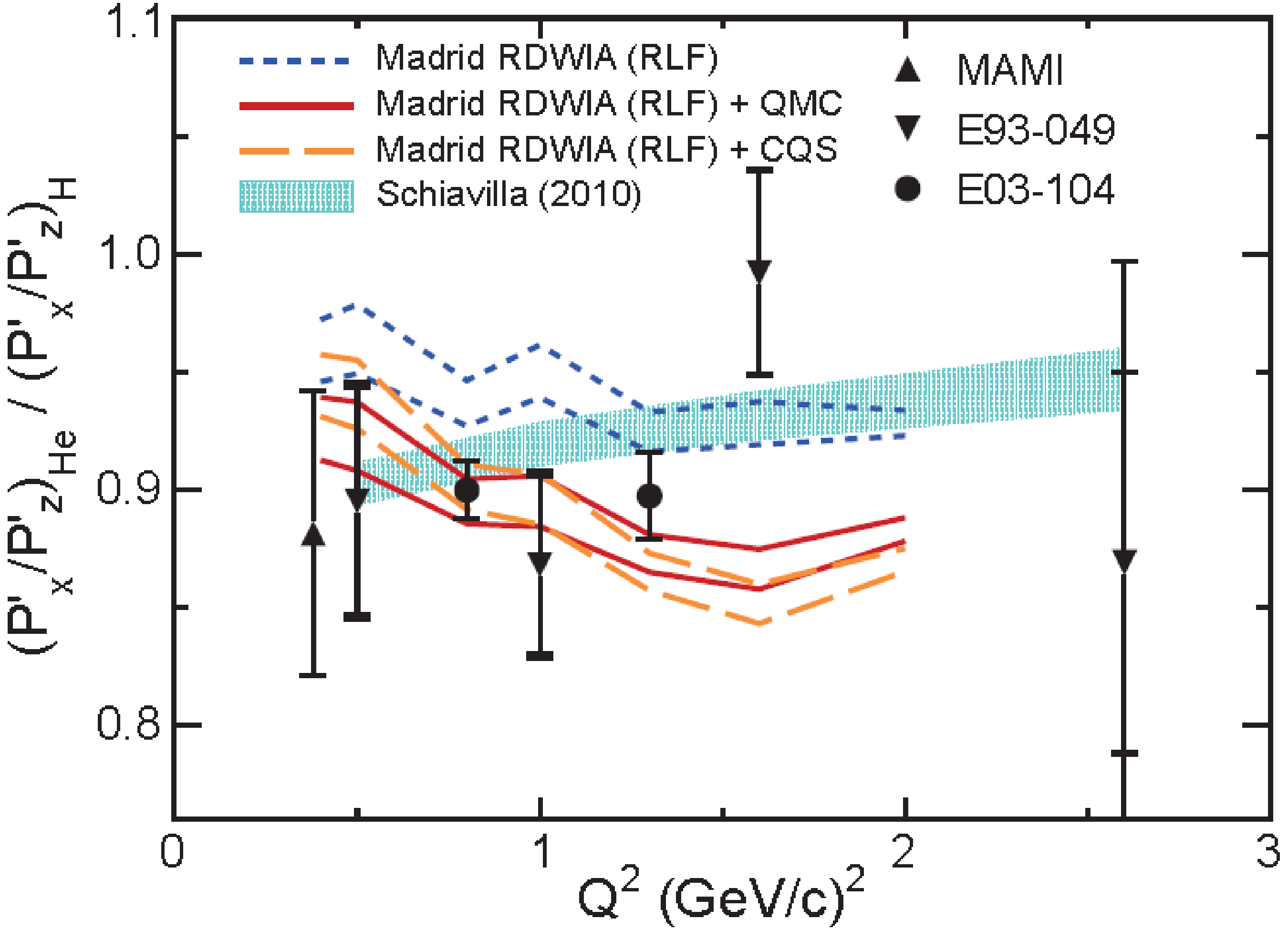


from - Cloet, Miller et al., arXiv:0903.1312

Jefferson Lab & Mainz : more from S. Strauch

Polarized ^{4}He(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)

ORIGIN …. in QMC Model

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

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)

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

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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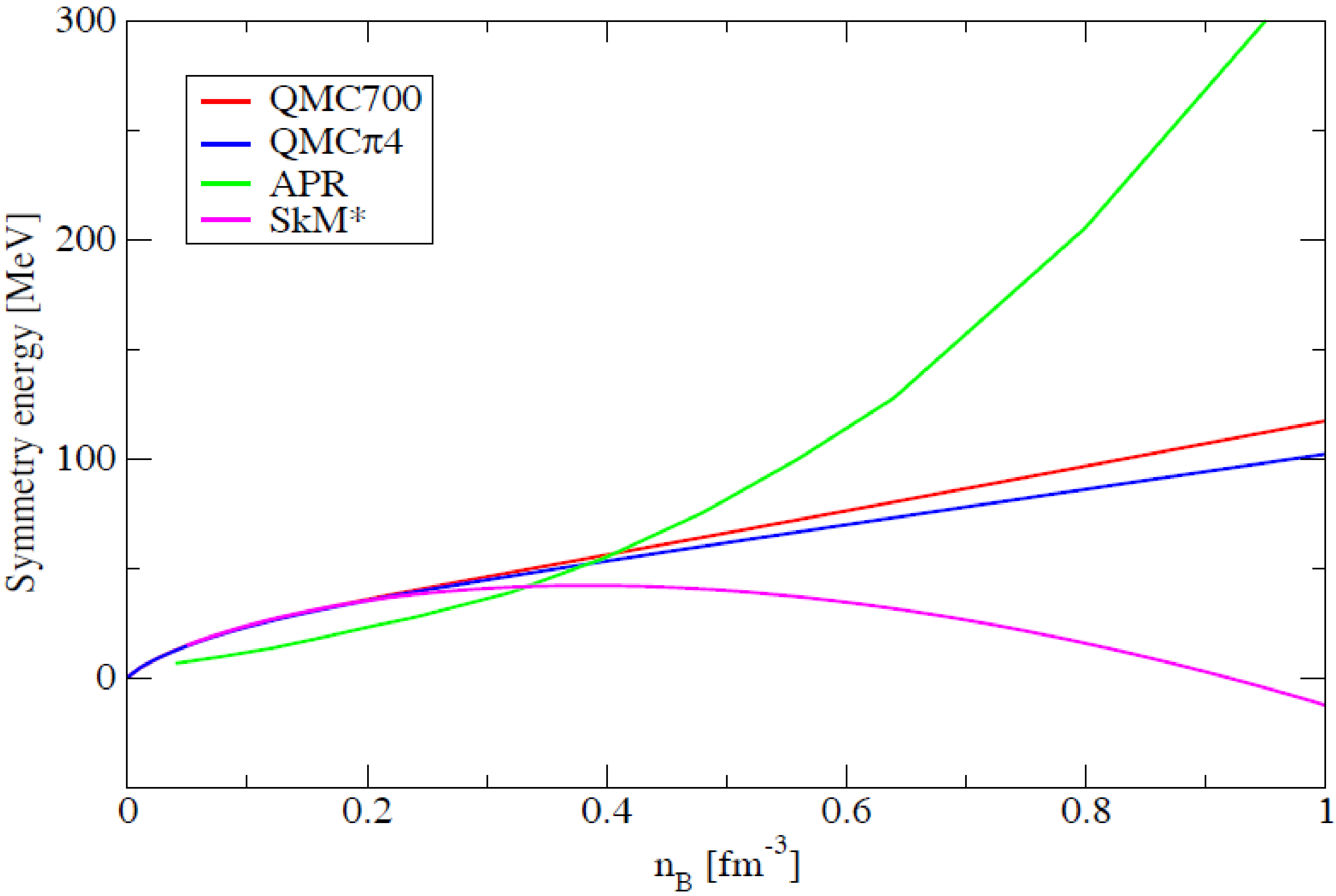
Symmetry Energy in β-Equilibrium (n,p,e,μ only)



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