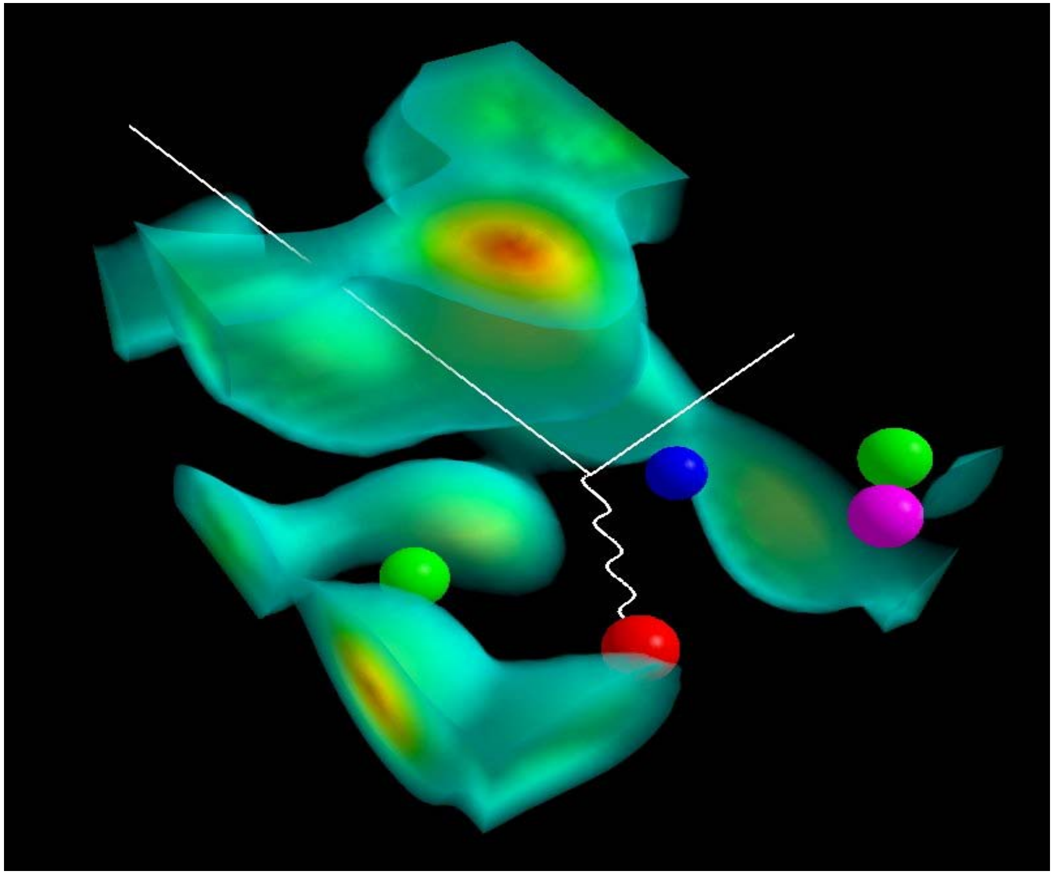
The Effective Hadron-Hadron Interaction in-Medium



Australian Government
Australian Research Council

Anthony W. Thomas

NN Interaction & the Nuclear Many-Body Problem
ICTS - TIFR : November 25th 2010

ADELAIDE UNIVERSITY AUSTRALIA

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A Personal View of the Problems

- Traditional non-relativistic potential models or EFT with expansion in powers of Q/m_ρ inapplicable at high density − even at $2\rho_0$

- Even at or below ρ_0 chiral EFT suffers from not knowing the relevant degrees of freedom
− typically start with N only; then discover the Δ; but are these the correct degrees of freedom?

- Phenomenological (“realistic” or “ab initio”) NN forces have many (>20) parameters and often serious cancellations − e.g. Jülich ΛN force

Problems (cont.)

- Traditional fit to NN force also needs lots of data (OK for NN but hopeless for HN) to determine parameters (within assumed form) and 3-body force fit to nuclear energy levels

- Finally, many fundamental problems such as EMC effect cannot be addressed

A Really Attractive Alternative

- **Start with a quark and gluon based model of hadron structure**

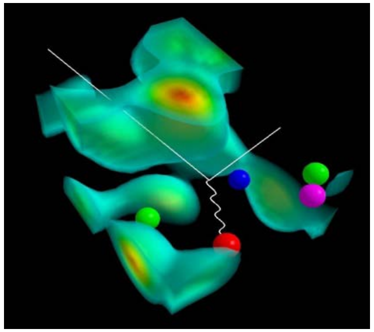
- **Imbed the hadron in-medium and solve (respecting special relativity) for its structure self-consistently at mean-field level (using Born-Oppenheimer approximation)**

- **Determine the small number of parameters (3 quark-meson coupling constants) from saturation of nuclear matter**

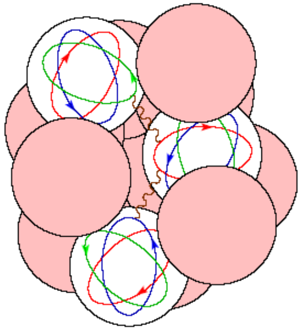
- **This yields the effective in-medium forces felt by every hadron that exists in the quark model chosen**

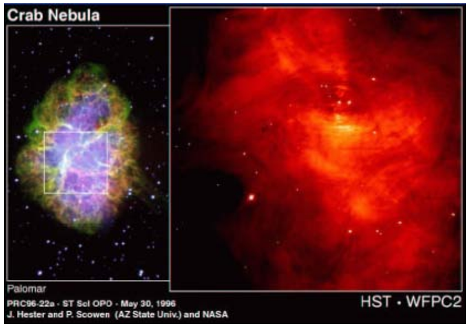
  − with <u>no</u> new parameters

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



QCD & hadron structure

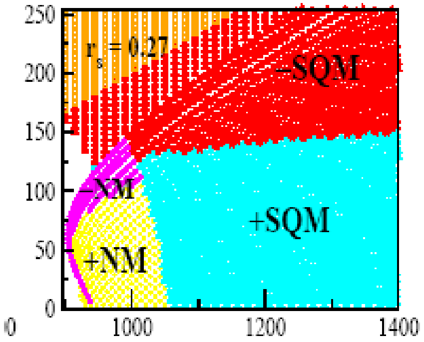




n star

∞ nuclear matter

Effective NN (and N Λ, N Ξ …) forces



quark matter

Finite nuclei
Hypernuclei

Where to find more information

- **Two major, recent papers:**

I. Guichon, Matevosyan, Sandulescu, Thomas,
Nucl. Phys. A772 (2006) 1.
II. Guichon and Thomas, Phys. Rev. Lett. 93 (2004) 132502

- **Built on earlier work on QMC: e.g.**

III. Guichon, Phys. Lett. B200 (1988) 235
IV. Guichon, Saito, Rodionov, Thomas,
Nucl. Phys. A601 (1996) 349

- **Major review of applications of QMC to many nuclear systems:**

V. Saito, Tsushima, Thomas,
Prog. Part. Nucl. Phys. 58 (2007) 1-167 (hep-ph/0506314)

Model Independent Features of NN Force

- Intermediate Range attraction is Lorentz scalar-isoscalar
  (since 70’s, dispersion relations, Paris potential…)

- Lorentz scalar force is strong (too strong in QHD)!

- Short distance repulsion is Lorentz vector
  (not so model independent BUT lots of support)

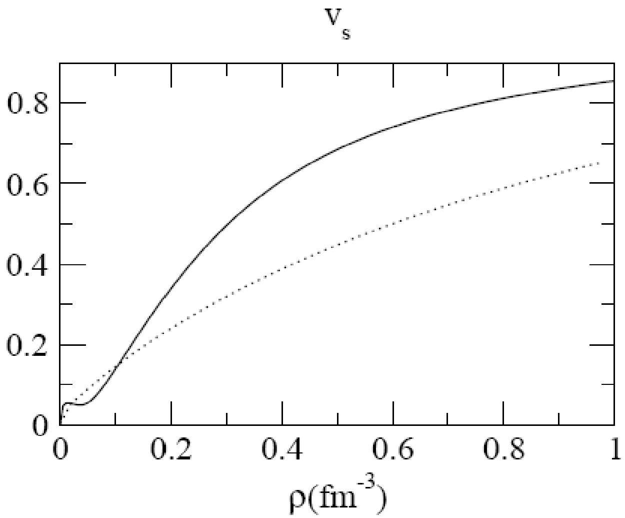
- At high density MFA gets to be accurate

- Classical implementation is Walecka model

  ⇒ $m_N^* / m_N \sim 0.5$ at ρ_0

Relativity Matters in Dense Matter

- Non-relativistic expansion in powers of k_F unlikely to be successful…..



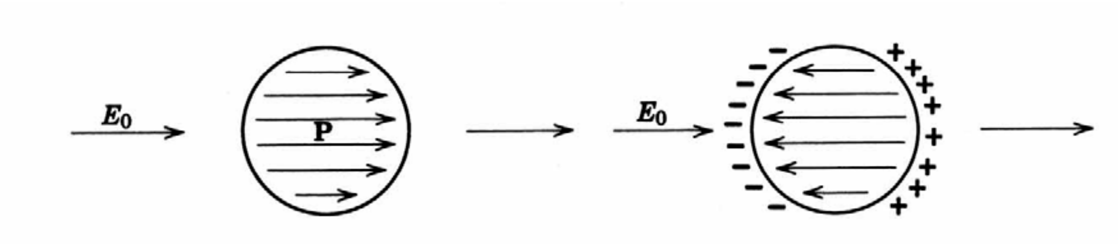
e.g. v_{sound} >c / 2 at $\rho = 2\ \rho_0$
and exceeds c at higher density;
- whereas v_{sound} = 0.3 c and never
exceeds c in relativistic treatment

- BUT what is missing in Walecka model (QHD)?

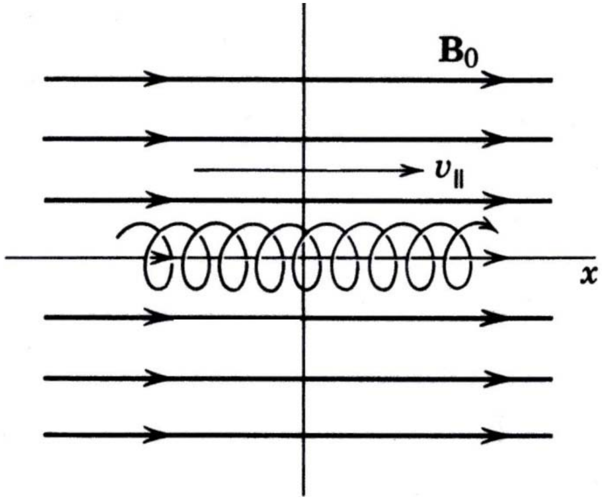
- Effect of $m_N^* = m_N / 2$ on internal structure of nucleon; this is a huge external field!

What happens if we put an atom in a strong electric field?

Jackson :



i.e. atom has a polarizability: its internal structure is rearranged in response to applied field



//’ly in applied magnetic field (indeed, in super strong field -e.g. n-star surface atoms & molecules essentially linear!)

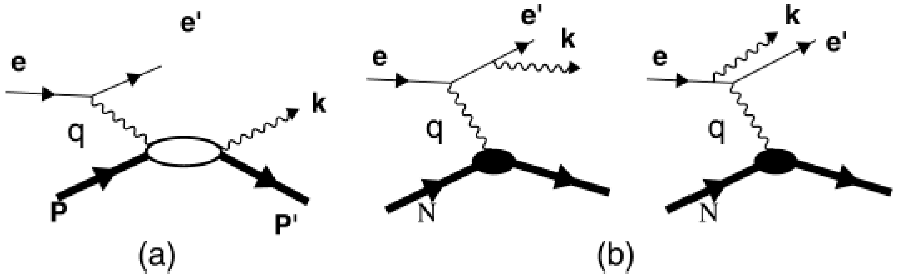
Electric & Magnetic Polarizabilities of Nucleon are Measured

e.g. Compton scattering:

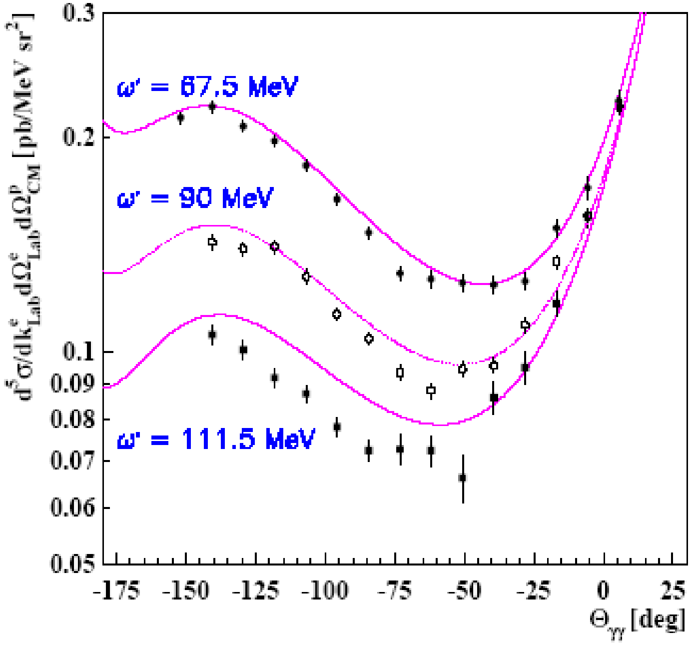
$$4\pi\,\alpha_E = 2\sum_{I\neq N}\frac{|\langle I|d_z|N\rangle|^2}{E_I - E_N}$$

$$\begin{aligned}\alpha_E^p &= (12.1 \pm 1.3)\cdot 10^{-4}\,\mathrm{fm}^3,\\ \beta_M^p &= (2.1 \mp 1.3)\cdot 10^{-4}\,\mathrm{fm}^3.\end{aligned}$$

Also Virtual Compton Scattering) GPs

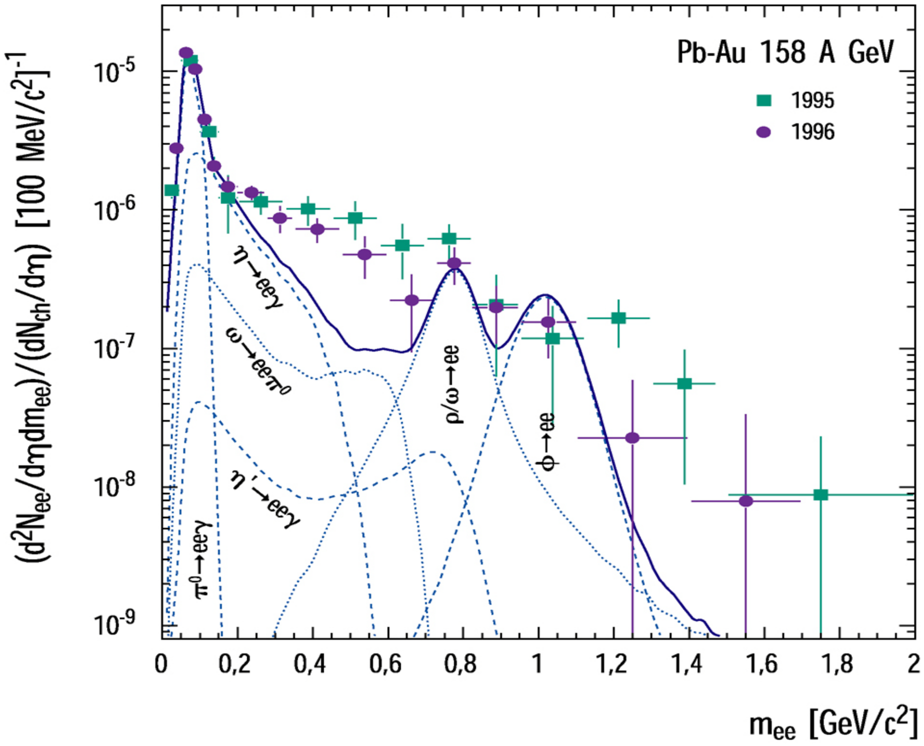


(a) (b)



So what?

Atoms respond to external E and B fields



- Nucleons respond to external E and B fields

- It is clear that nucleons must respond to large scalar fields known to exist in-medium

- This leads to a mass shift that is non-linear in mean scalar field : scalar polarizability

Fundamental Question: “What is the Scalar Polarizability of the Nucleon?”

Nucleon response to a chiral invariant scalar field is then a nucleon property of great interest…

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

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.

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: $\int_{Bag} d\vec{r}\,\overline{\psi}(\vec{r})\psi(\vec{r})$

SELF-CONSISTENCY

and hence mean scalar field changes…

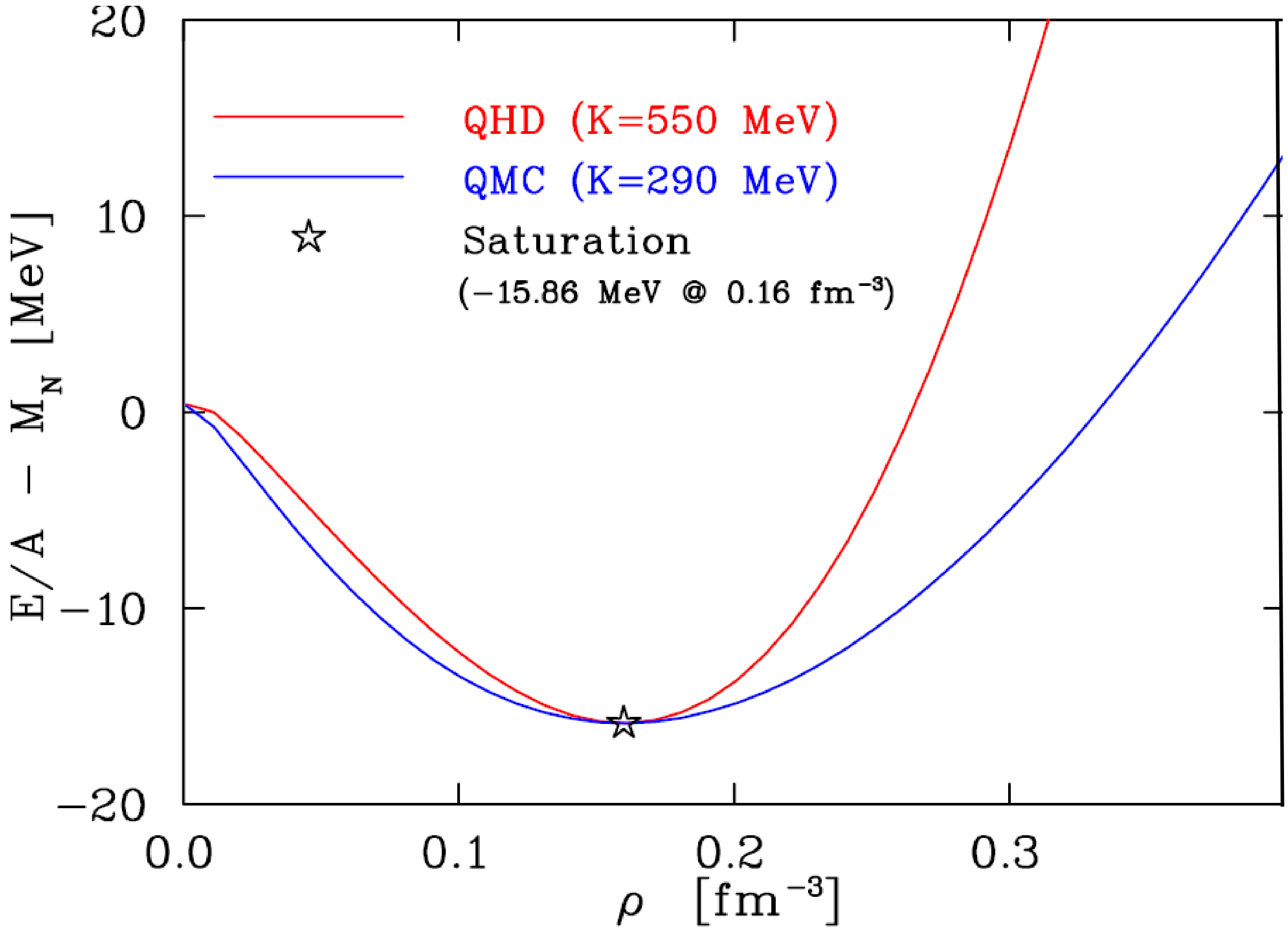
and hence quark wave function changes….

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)

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

Saturation of symmetric nuclear matter

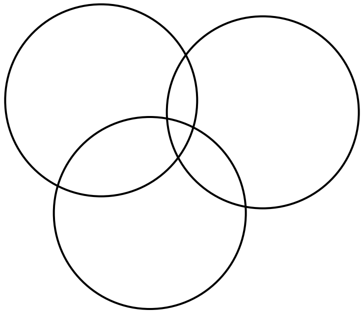


Summary : Scalar Polarizability

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

- In nuclear matter this is the only place the internal structure of the nucleon enters in MFA

- 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 polarisability")

- 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 (and m_σ ambiguous when theory is quantised)

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

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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 recently:
  the trick is to apply a chiral invariant scalar field
  − do indeed find polarisability opposing applied σ field

18th Nishinomiya Symposium: nucl-th/0411014
− published in Prog. Theor. Phys.

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**

In Paper I: Guichon and Thomas, Phys. Rev. Lett. 93, 132502 (2004)

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

- equivalent to QMC model (required an expansion around $\sigma = 0$)

Comparison Between Skyrme III and QMC

	QMC	QMC	SkIII	QMC(N=3)
$m_\sigma (MeV)$	500	600		600
$t_0 (MeV\ fm^3)$	-1071	-1082	-1129	-1047
x_0	0.89	0.59	0.45	0.61
$t_3 (MeV\ fm^6)$	16620	14926	14000	12996
M_{eff}/M	.915	.814	.763	.821
$5t_2 - 9t_1 (MeV\ fm^5)$	-7622	-4330	-4030	-4036
$W_0 (MeV\ fm^5)$	118	97	120	91

Three-body force, arising from scalar polarizability, agrees naturally with force (t_3) found phenomenologically - origin is same as that in atomic and molecular physics!

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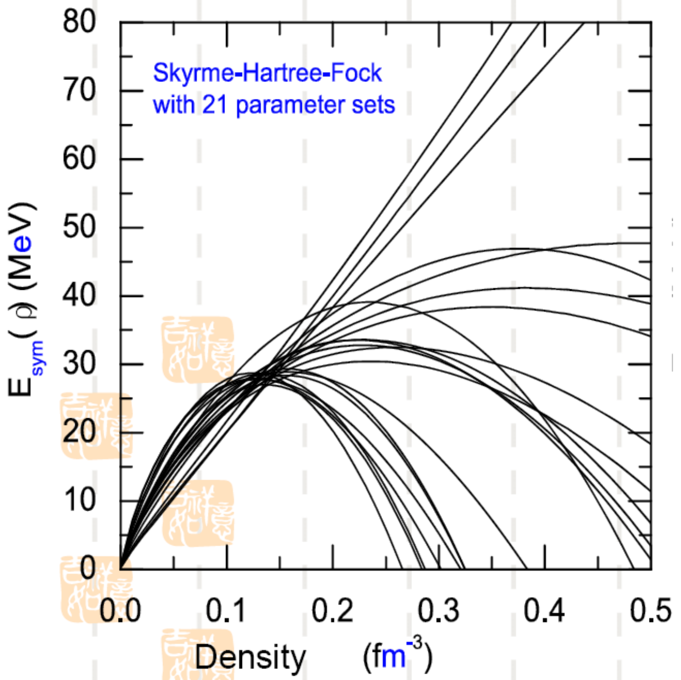
Density Dependent Skyrme Force(s) are now more widely used

$$
\begin{aligned}
E_o = \frac{\mathcal{E}}{\rho} = {} & \frac{3\hbar^2}{10M}\left(\frac{3\pi^2}{2}\right)^{2/3}\rho^{2/3}H_{5/3} + \frac{t_0}{8}\rho[2(x_0+2)-(2x_0+1)H_2] \\
& + \frac{1}{48}\sum_{i=1}^{3} t_{3i}\rho^{\sigma_i+1}[2(x_{3i}+2)-(2x_{3i}+1)H_2] + \frac{3}{40}\left(\frac{3\pi^2}{2}\right)^{2/3}\rho^{5/3}(aH_{5/3}+bH_{8/3}) \\
& + \frac{3}{40}\left(\frac{3\pi^2}{2}\right)^{2/3}\rho^{8/3}[t_4(x_4+2)H_{5/3}-t_4(x_4+0.5)H_{8/3}].
\end{aligned}
$$

$$
\begin{aligned}
a &= t_1(x_1+2)+t_2(x_2+2), \\
b &= \frac{1}{2}\left[t_2(2x_2+1)-t_1(2x_1+1)\right], \\
H_n(y) &= 2^{n-1}[y^n+(1-y)^n]. \quad y = Z/A
\end{aligned}
$$

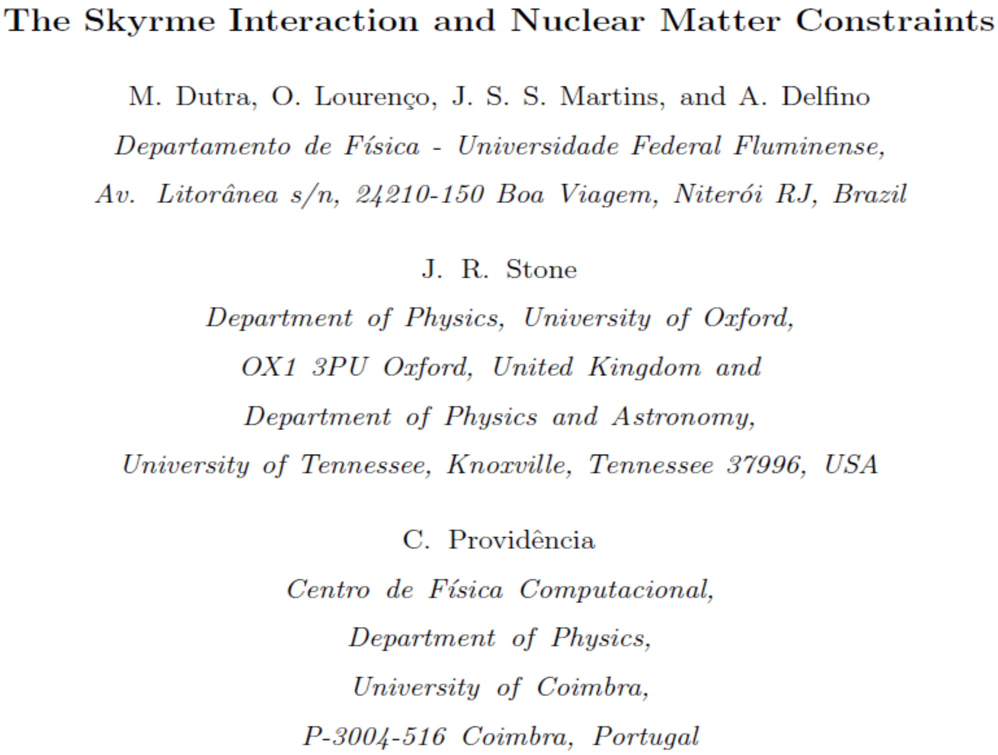


Skyrme forces fit 10-15 parameters to properties of symmetric nuclear matter as well as selected sets of other data

For example:

- **Sly : n-matter, n-stars, large-A nuclei**
- **SkI : isotope shifts in Pb region**
- **SkM* : finite nuclei & actinide fission barriers**
- **SSk : nuclear masses**

In past few weeks: 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

J. R. Stone
Department of Physics, University of Oxford,
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Department of Physics and Astronomy,
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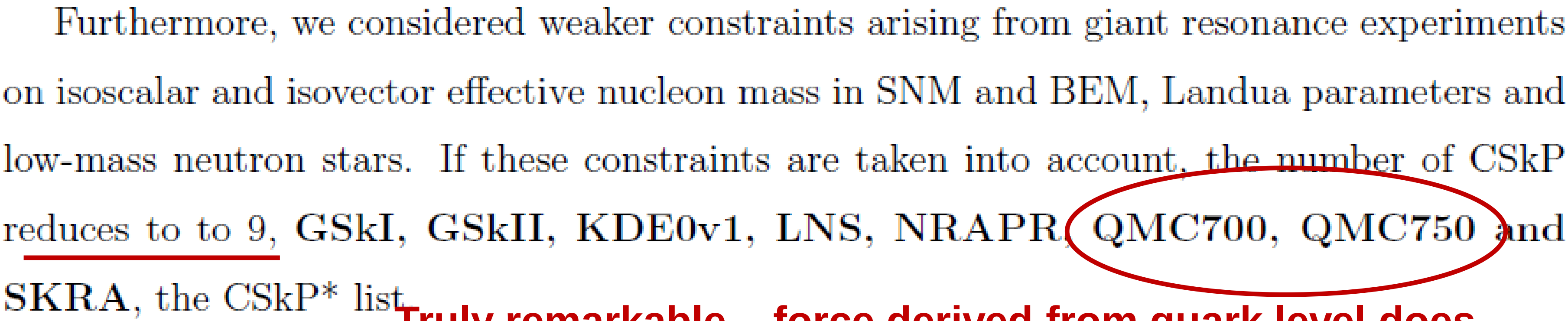
C. Providência
Centro de Física Computacional,
Department of Physics,
University of Coimbra,
P-3004-516 Coimbra, Portugal

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 4-5 times # parameters!

Constraints from Heavy Ion Reactions

– from Dutra et al. (2010)

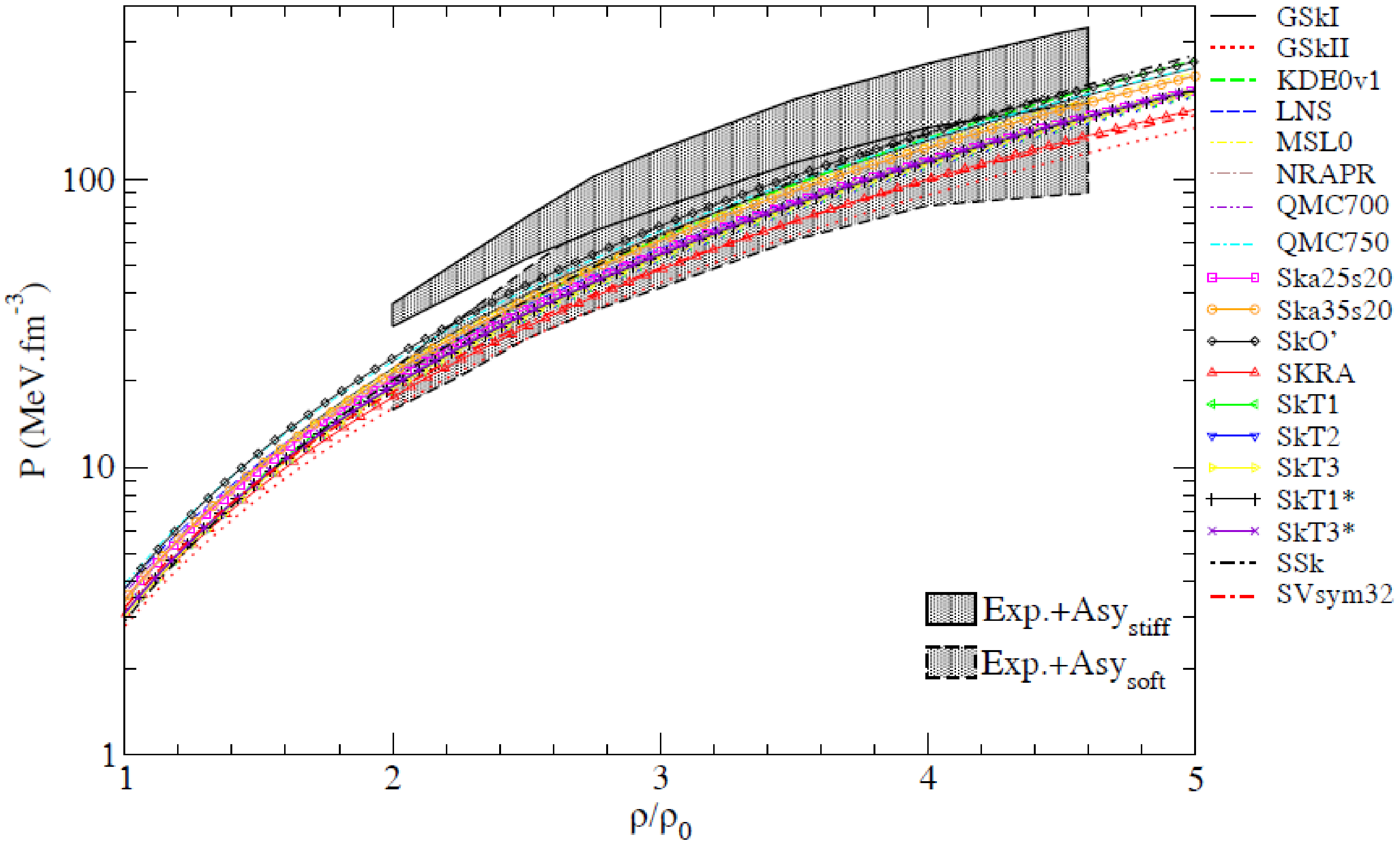
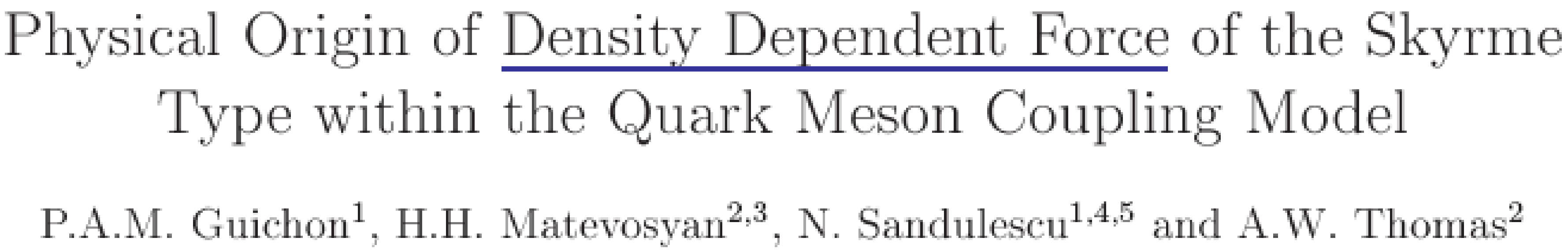


FIG. 4: (color online). Constraint **PNM2**: Pressure in the pure neutron matter as a function of density in the region 2 ¡ $\frac{\rho}{\rho_o}$ ¡ 4.6. For detailed explanation see Ref. [24].

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

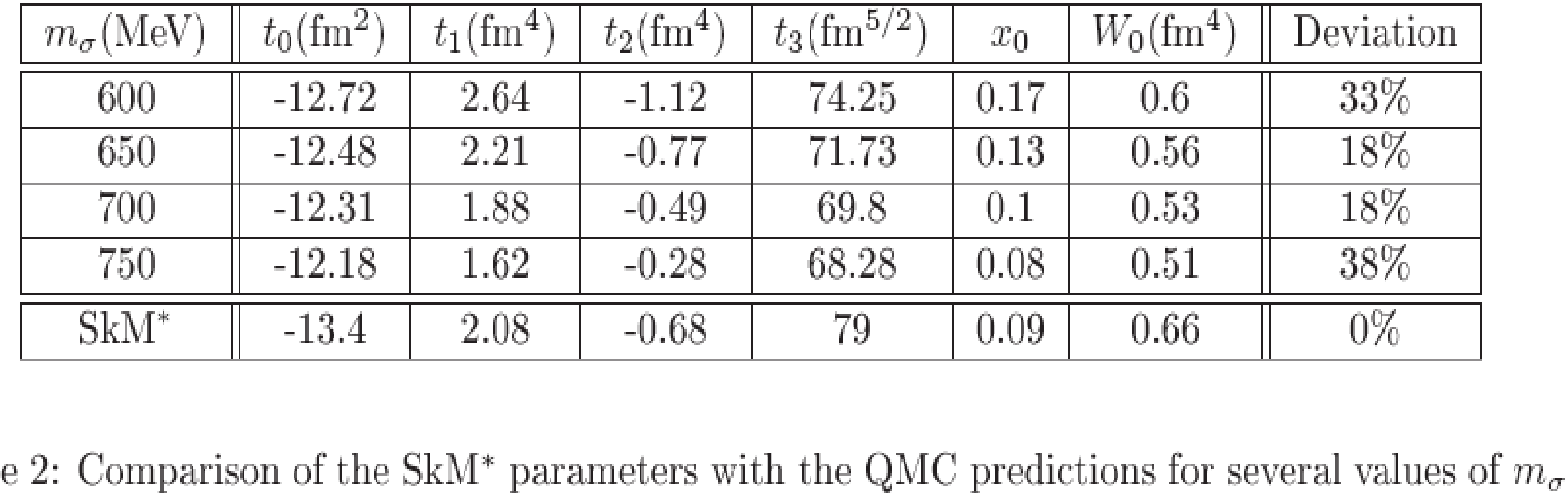


Physical Origin of Density Dependent Force of the Skyrme Type within the Quark Meson Coupling Model

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

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

No longer need to expand around < σ > = 0



m_σ(MeV)	t_0(fm^2)	t_1(fm^4)	t_2(fm^4)	t_3(fm$^{5/2}$)	x_0	W_0(fm^4)	Deviation
600	-12.72	2.64	-1.12	74.25	0.17	0.6	33%
650	-12.48	2.21	-0.77	71.73	0.13	0.56	18%
700	-12.31	1.88	-0.49	69.8	0.1	0.53	18%
750	-12.18	1.62	-0.28	68.28	0.08	0.51	38%
SkM*	-13.4	2.08	-0.68	79	0.09	0.66	0%

Table 2: Comparison of the SkM* parameters with the QMC predictions for several values of m_σ

BUT density functional not exactly the same
– QMC yields rational forms

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Check directly vs data

- **That is, apply new effective force directly to calculate nuclear properties using Hartree-Fock (as for usual well known force)**

	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

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

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

Check directly vs data

- That is, apply new effective force directly to calculate nuclear properties using Hartree-Fock (as for usual well known force)

	E_B (MeV, exp)	E_B (MeV, QMC)	r_c (fm, exp)	r_c (fm, QMC)
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^{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:

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

○ highlights scalar polarizability

Check directly vs data

- **That is, apply new effective force directly to calculate nuclear properties using Hartree-Fock (as for usual well known force) – for example:**

	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

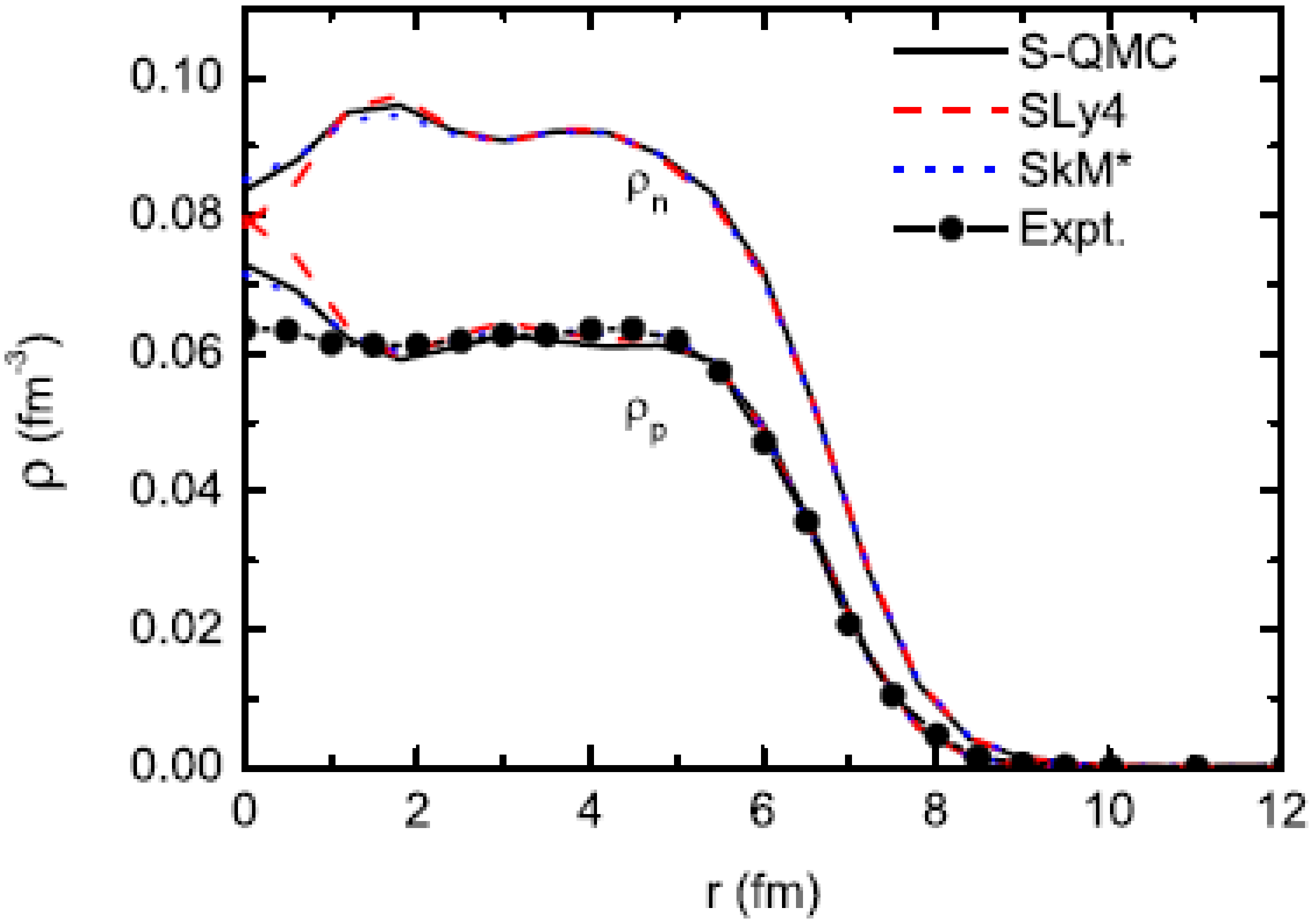
- **In comparison with the SkM force:**

$$\mathcal{H}_0 + \mathcal{H}_3 = \frac{\rho^{\frac{1}{6}}\, t_3 \left(2\,\rho^2 - {\rho_n}^2 - {\rho_p}^2\right)}{24} + \frac{t_0 \left(\rho^2 \left(2 + x_0\right) - \left(1 + 2\,x_0\right) \left({\rho_n}^2 + {\rho_p}^2\right)\right)}{4}$$

and full energy functional in both cases is:

$$< H(\vec{r}) >= \rho M + \frac{\tau}{2M} + \mathcal{H}_0 + \mathcal{H}_3 + \mathcal{H}_{eff} + \mathcal{H}_{fin} + \mathcal{H}_{so}$$

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

Finally: Apply to Shell Structure as N – Z +

- **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.)

Great Start: What's Next

Removed small σ field approximation

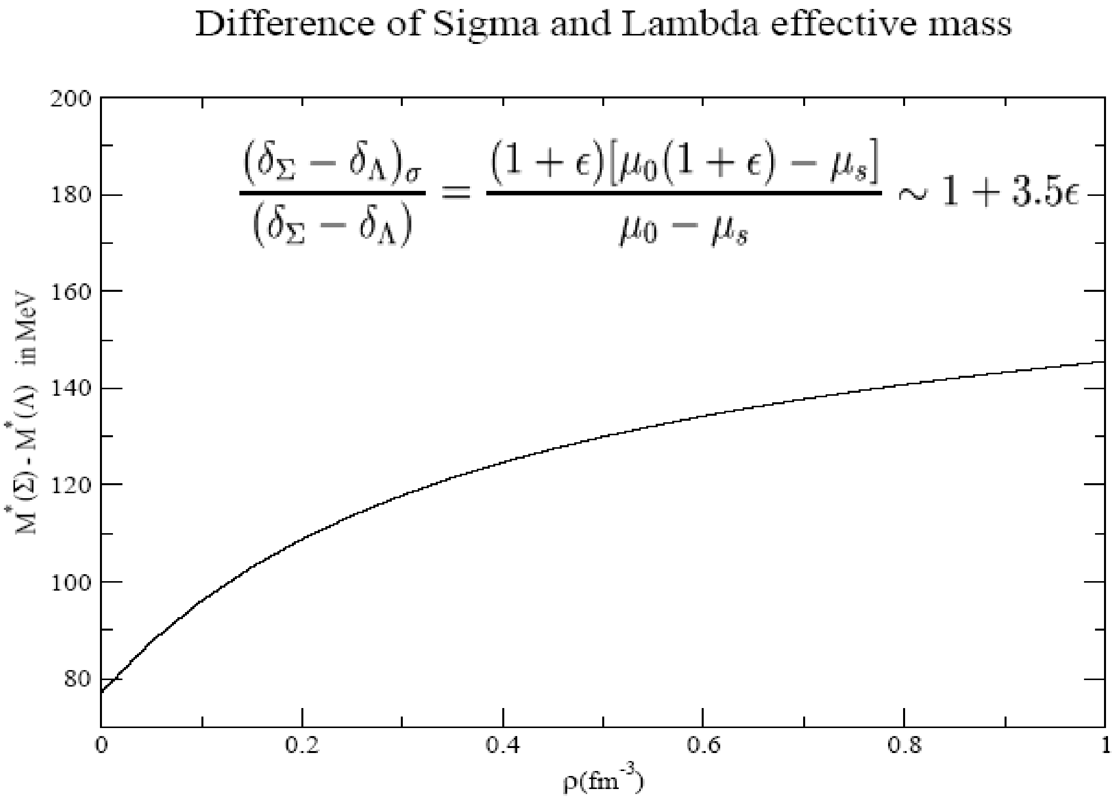
- **Derived density-dependent forms**
- **Added the pion**
- **Derived Λ N, Σ N, Λ Λ … effective forces in-medium with no additional free parameters**
- **Hence attack dense hadronic matter, n-stars, transition from NM to QM or SQM with more confidence**

Hyperons

- Λ, Σ and Ξ have: one s-quark (S=0 or S=1 light quarks) or two s-quarks – all in s-state (same octet as N)
- Masses in free space 1115 MeV (c.f. 940 MeV for p) 1190 MeV and 1315 MeV
- 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?

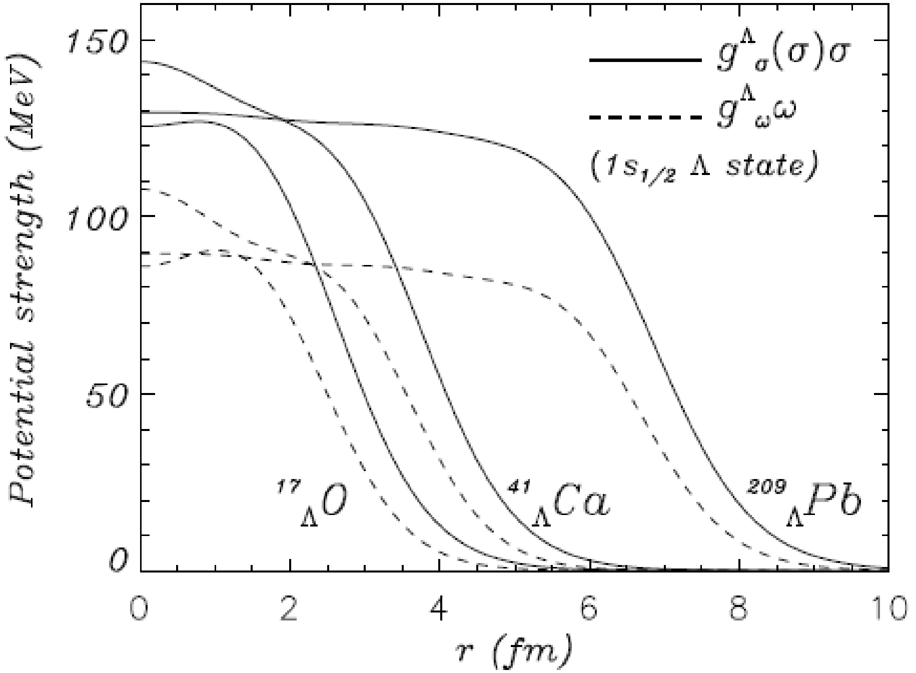
Medium Modification of Hyperfine Interaction

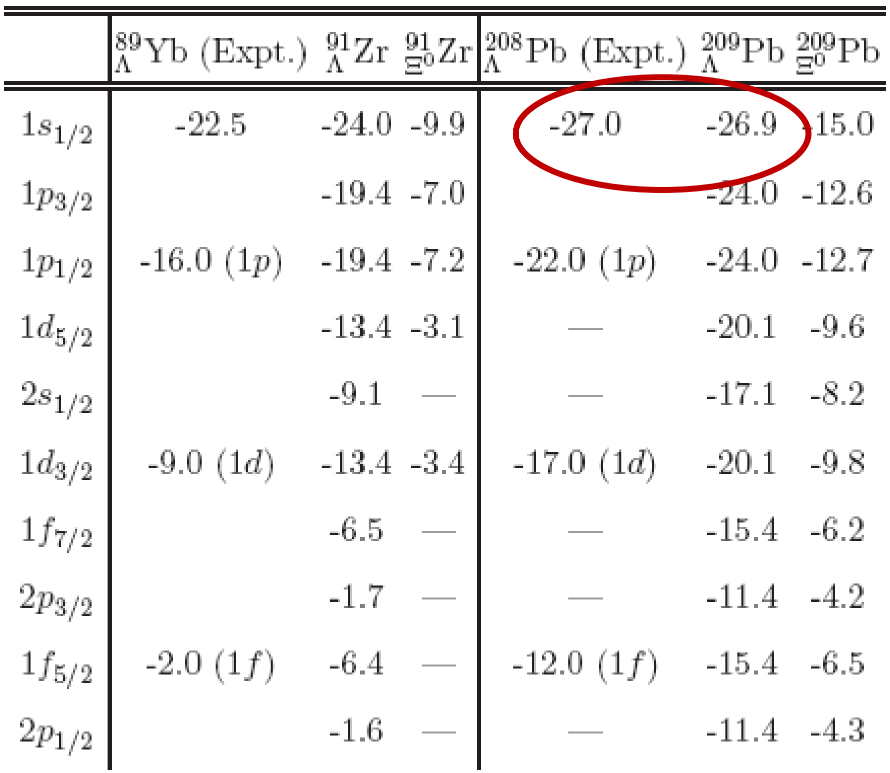
N - Δ and Σ - Λ splitting arise from one-gluon-exchange in MIT Bag Model : as σ ↑ so does this splitting…



Guichon, Thomas, Tsushima: nucl-th/0712.1925

Finite Hypernuclei in new QMC Model





	$^{89}_{\Lambda}$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 (1*p*)	-19.4	-7.2	-22.0 (1*p*)	-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 (1*d*)	-13.4	-3.4	-17.0 (1*d*)	-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 (1*f*)	-6.4	—	-12.0 (1*f*)	-15.4	-6.5
$2p_{1/2}$		-1.6	—	—	-11.4	-4.3

Λ energy levels good; spin-orbit force naturally suppressed;

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

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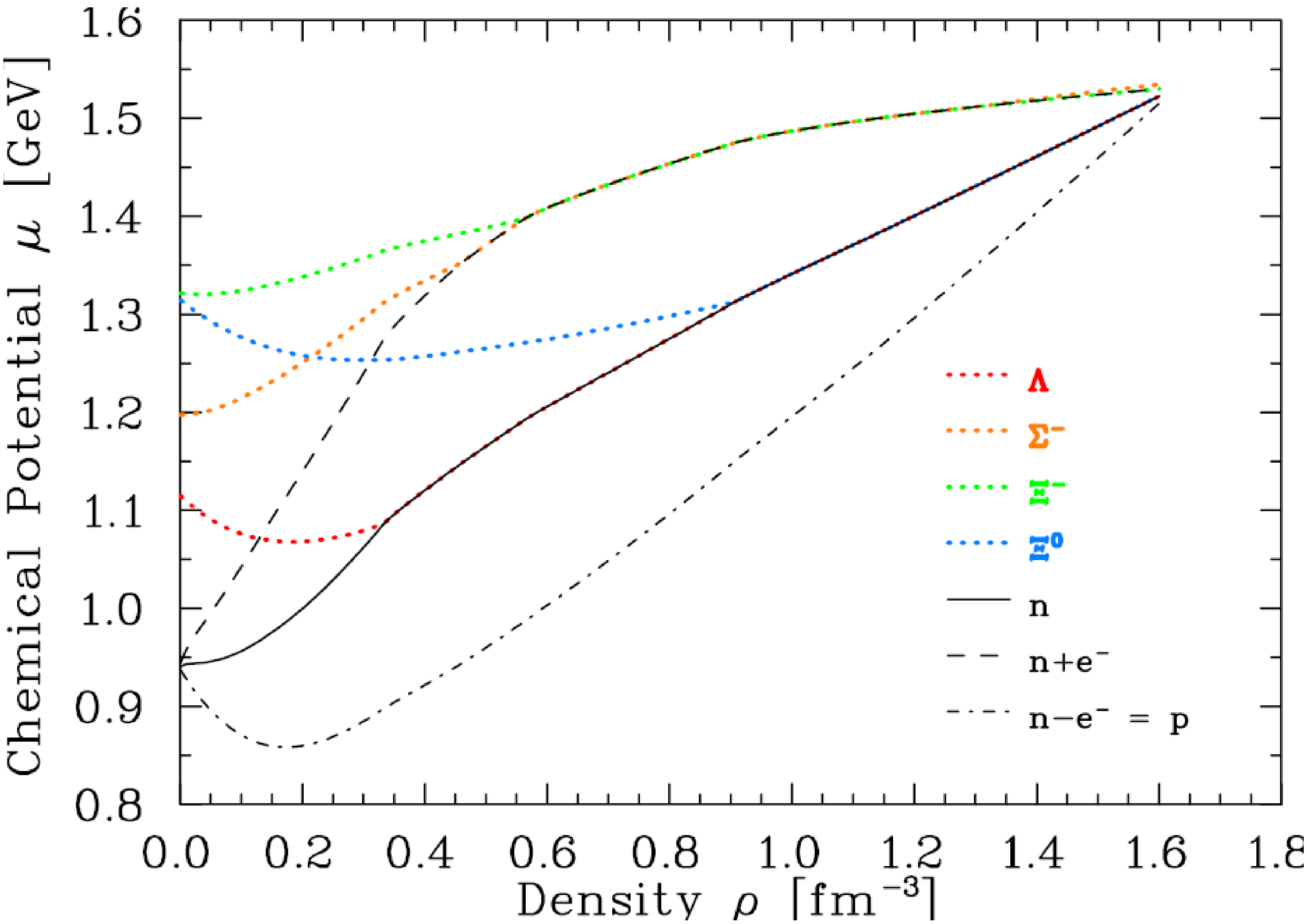
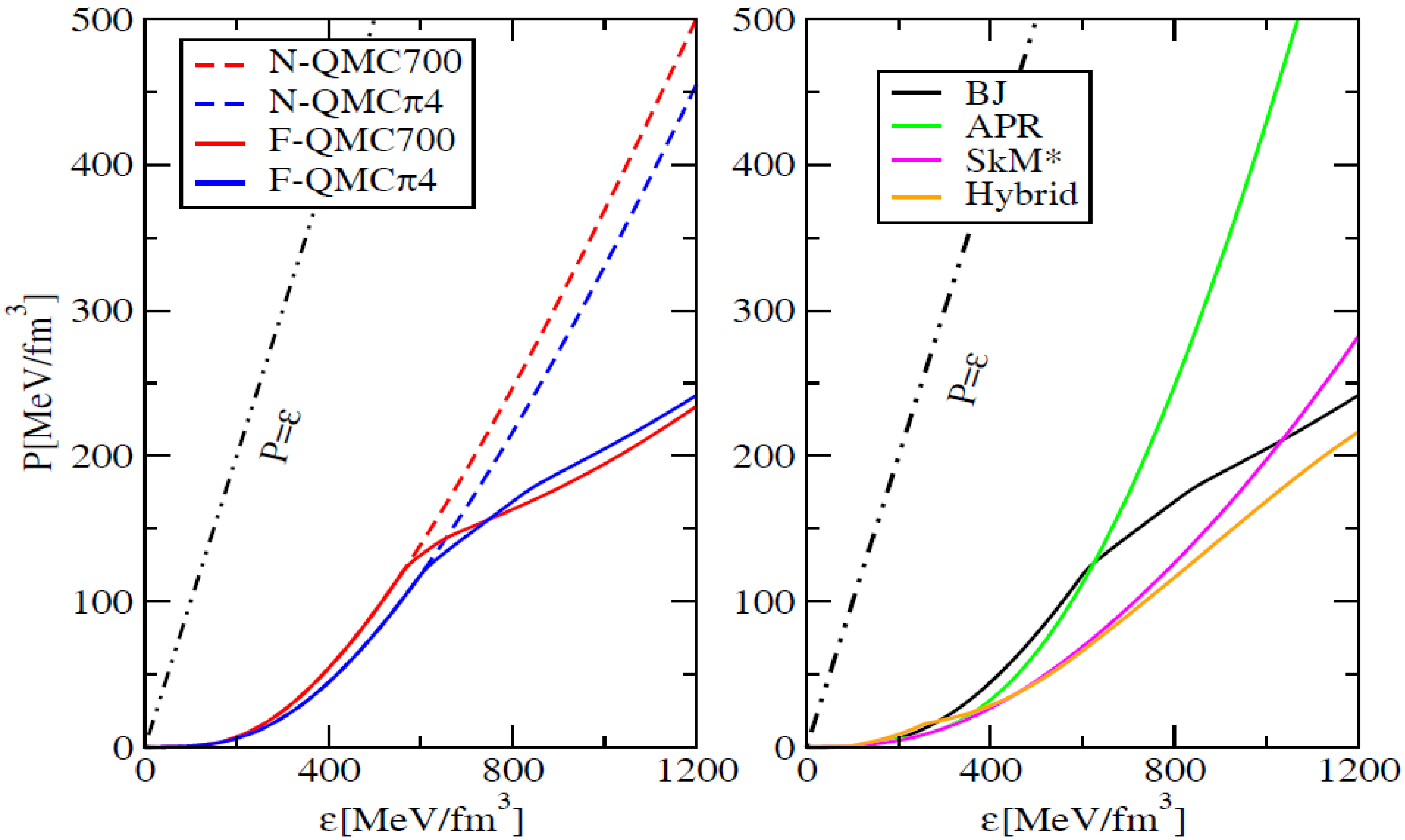
Nuclear Matter in β-Equilibrium



Equations of State



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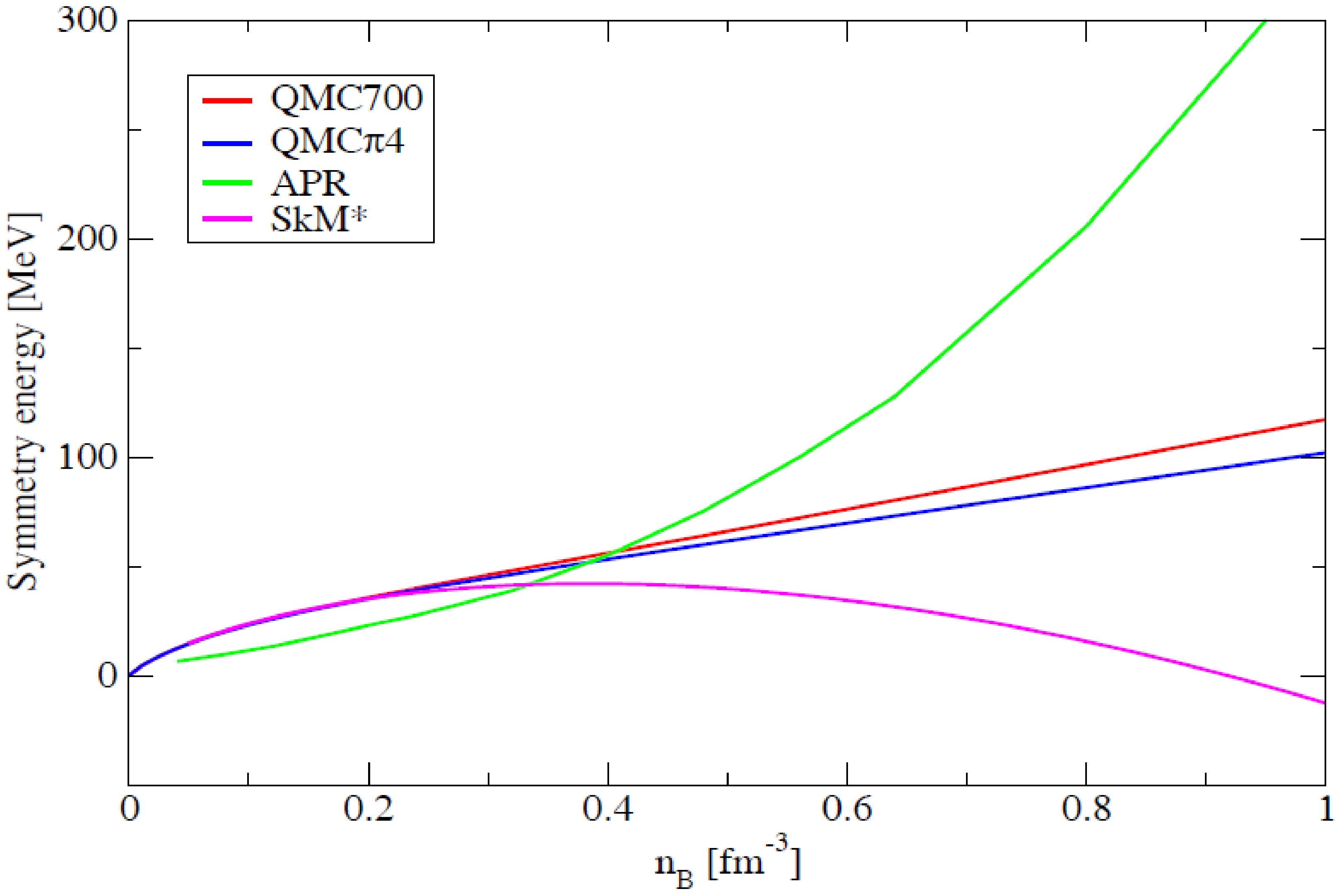
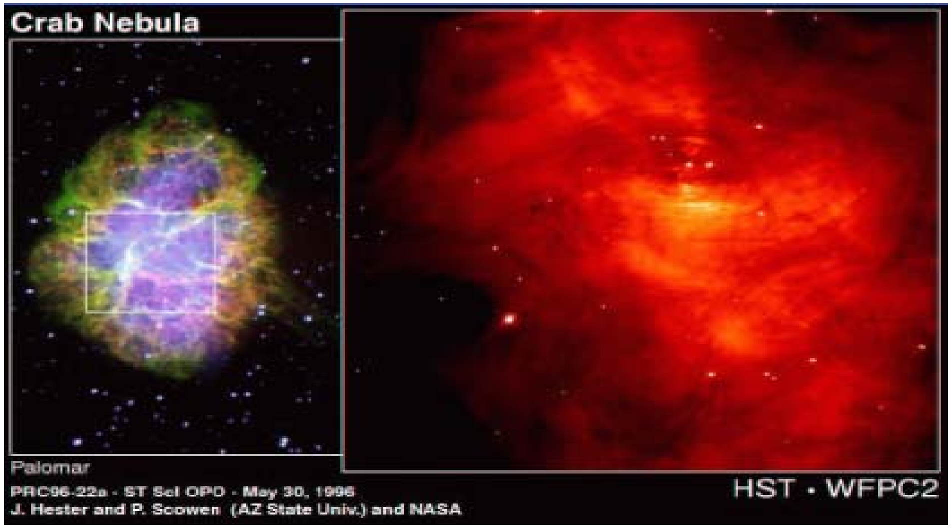
Symmetry Energy in β-Equilibrium (n,p,e,μ only)

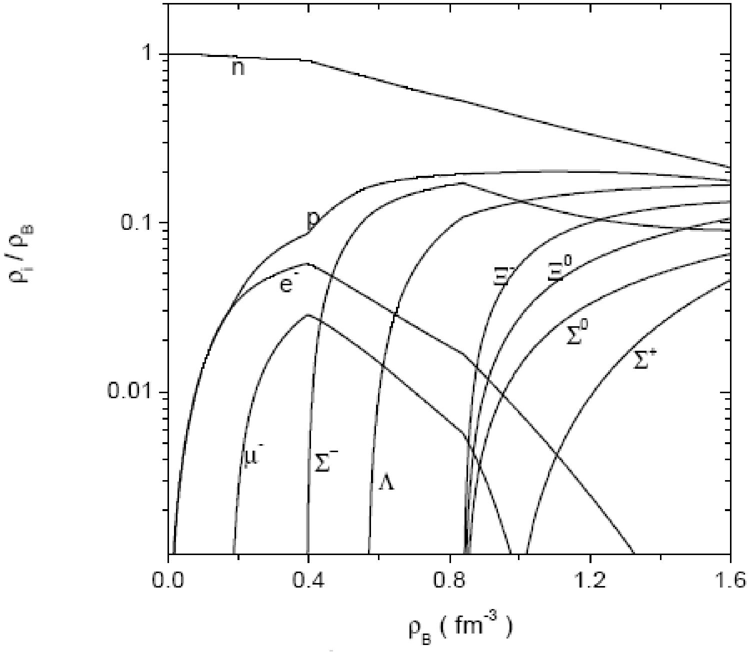


- **Hyperons enter at just 2-3 ρ_0**

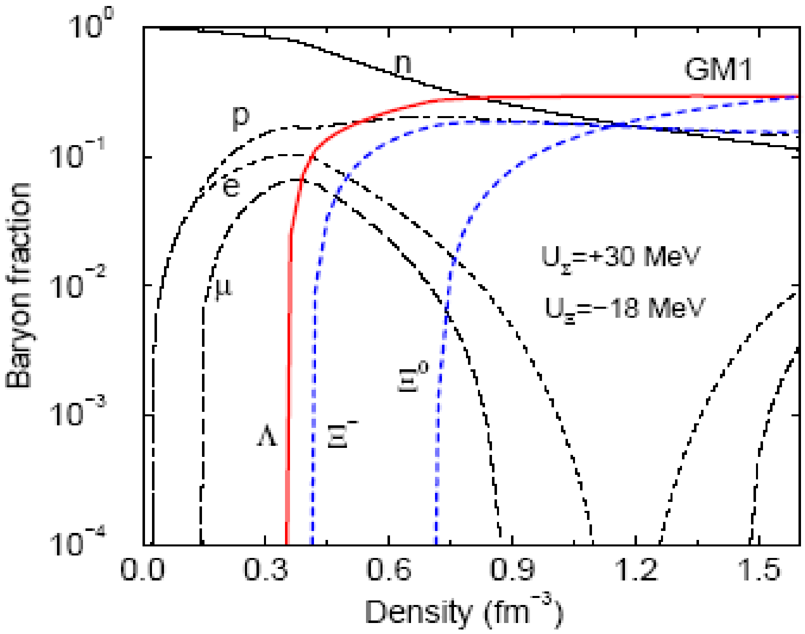
- **Hence need effective Σ-N and Λ-N forces in this density region!**

- **Hypernuclear data is important input (J-PARC, FAIR, JLab)**



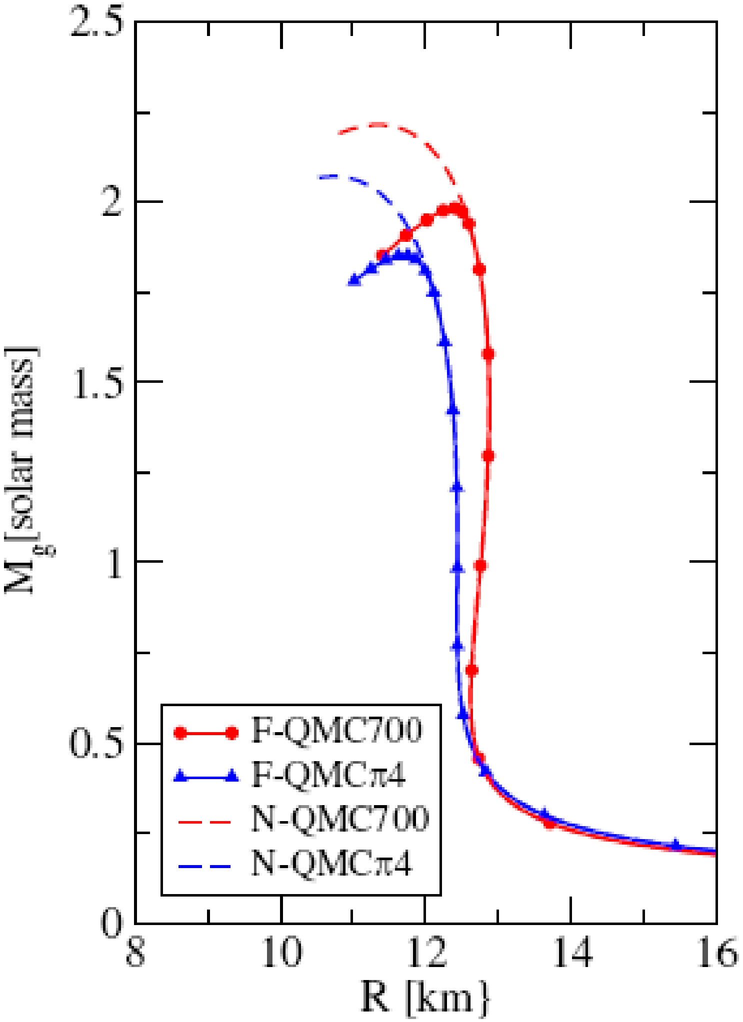


?

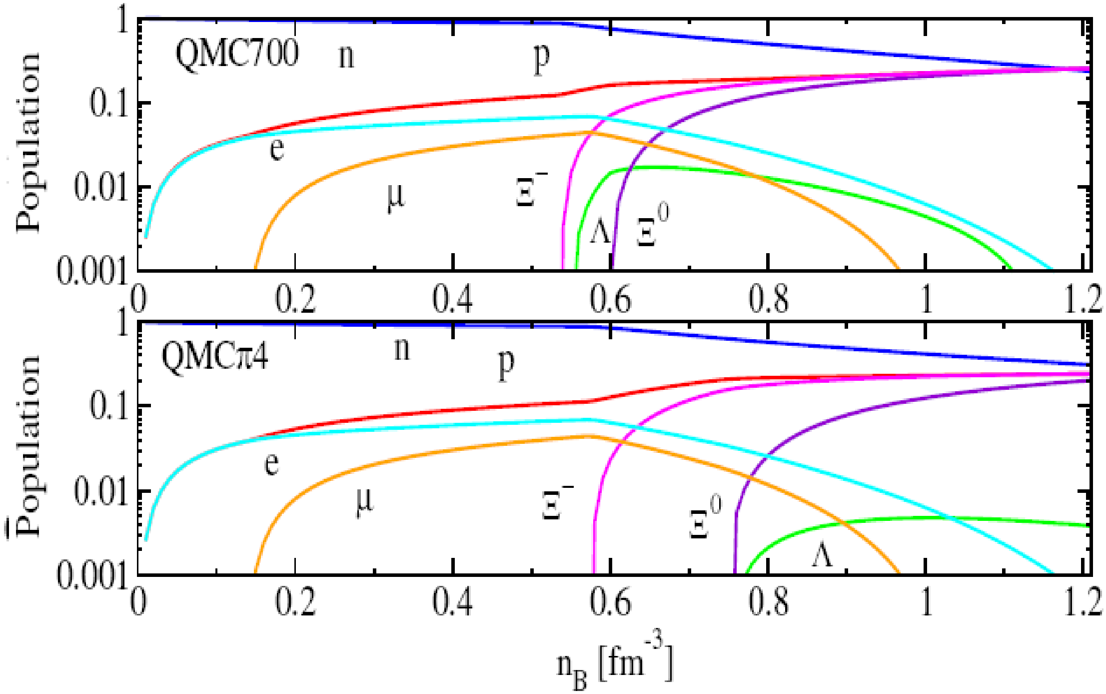


From Schaffner-Bielich (2005)

Consequences for Neutron Star



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



N-star Masses and Radii

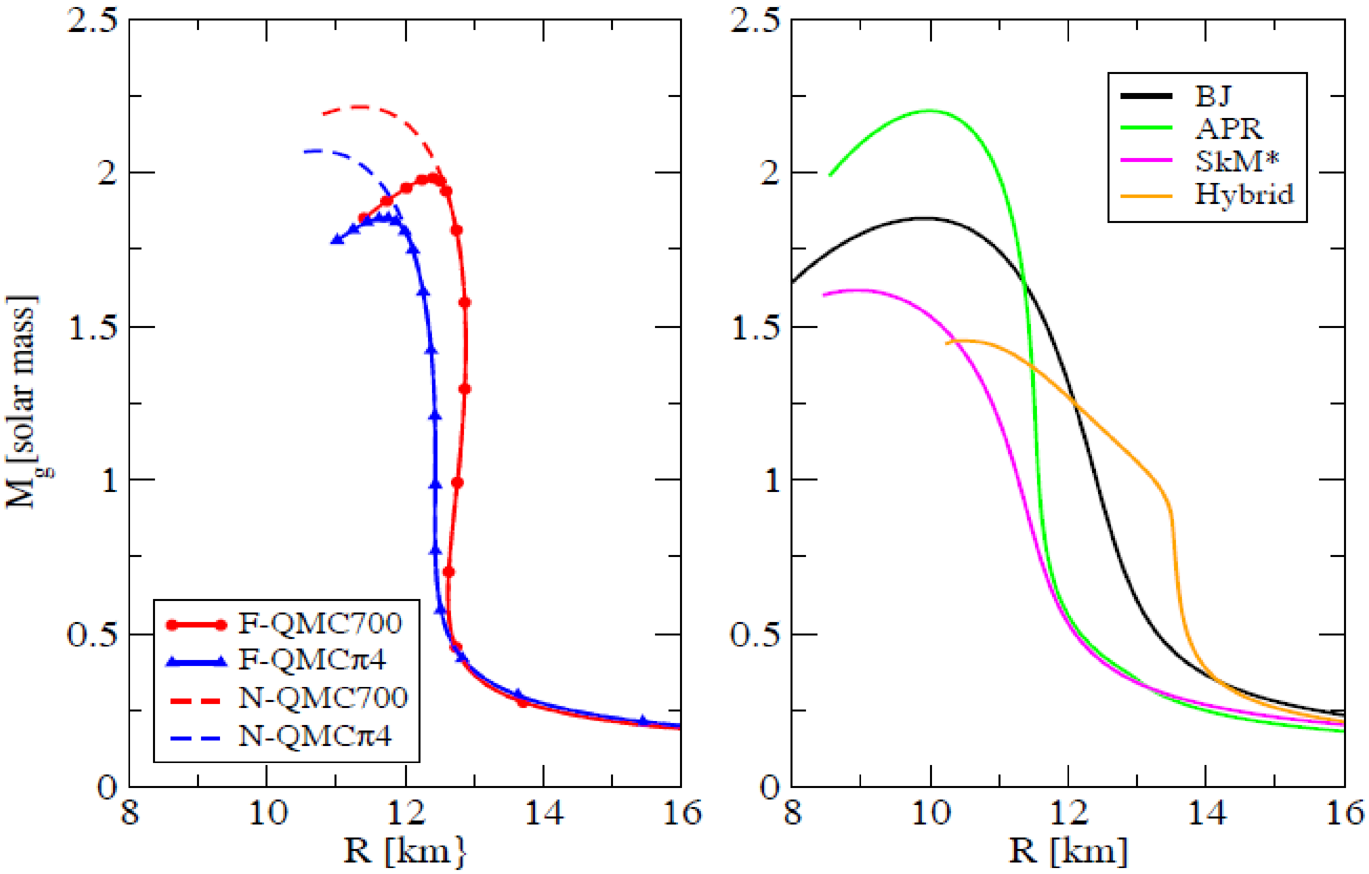


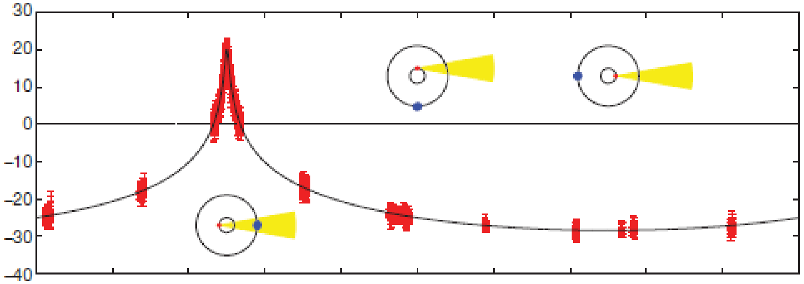
Fig. 5. The gravitational masses of non-rotating neutron-star models (measured in solar masses) plotted against radius (in kilometers), calculated for selected QMC EoS

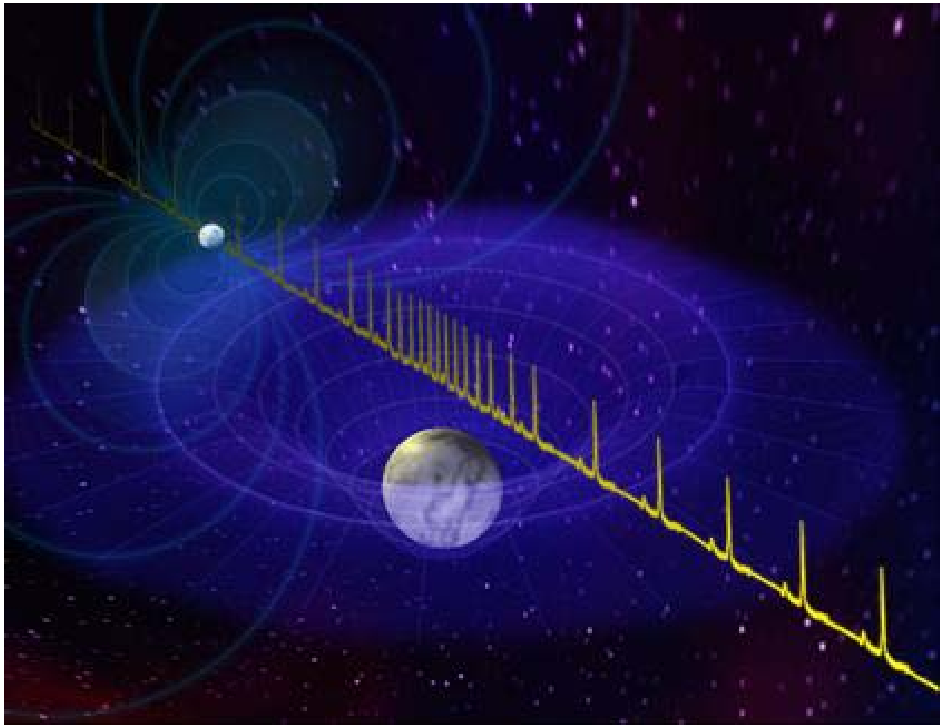
LETTER

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]



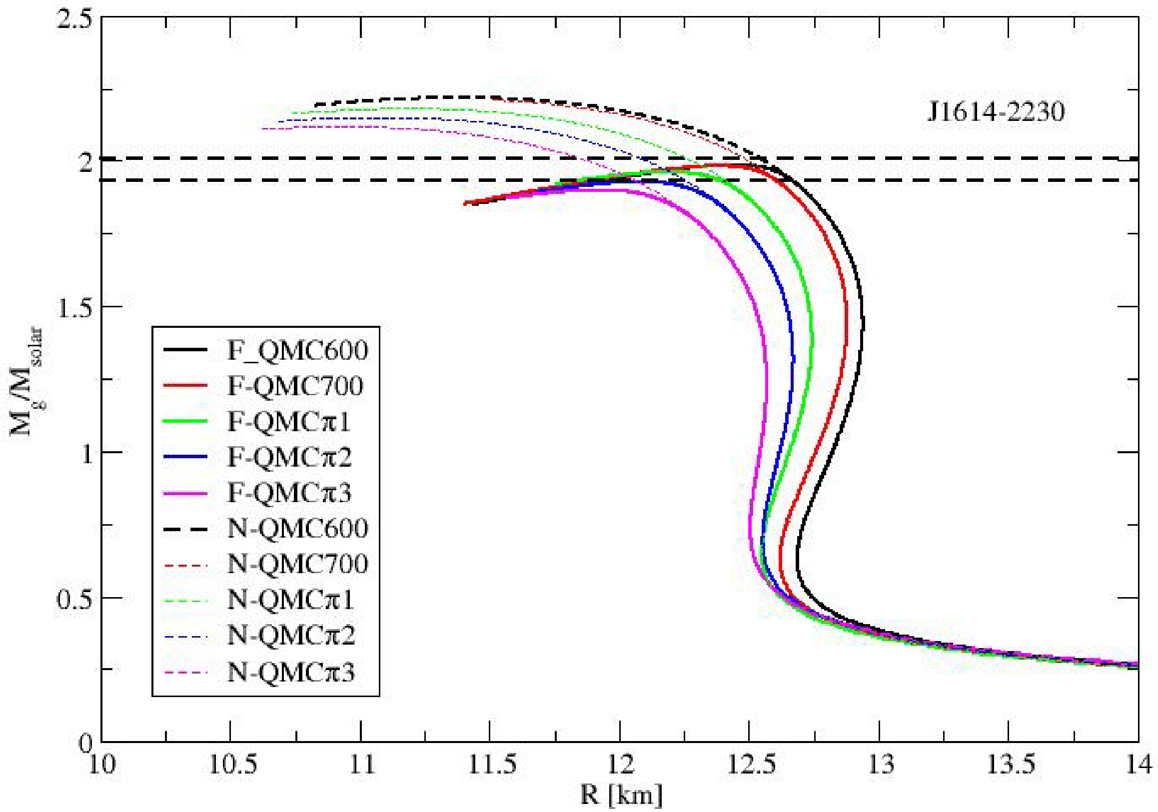


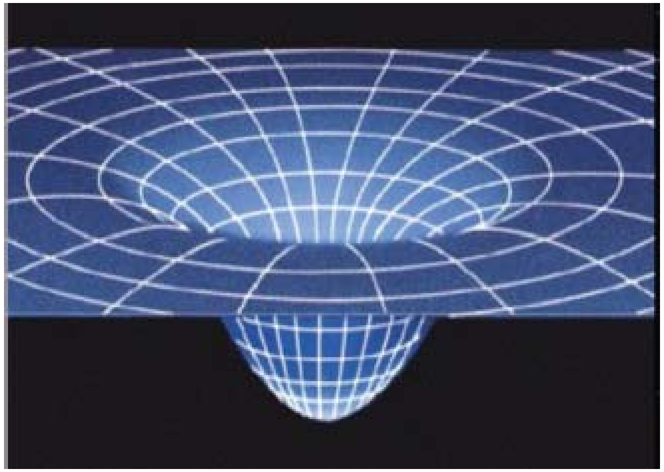
Report a very accurate pulsar mass much larger than seen before : 1.97 ± 0.04 solar mass

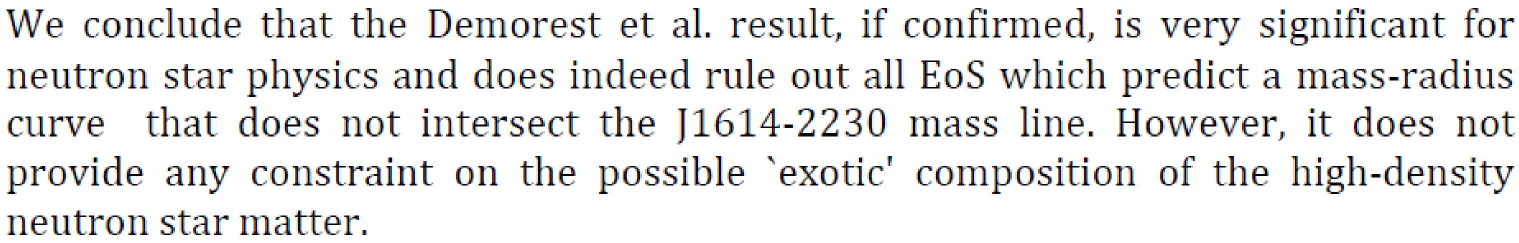
Claim it rules out hyperons (particles with strange quarks)

J1614-2230

Just 3 years ago*....







We conclude that the Demorest et al. result, if confirmed, is very significant for neutron star physics and does indeed rule out all EoS which predict a mass-radius curve that does not intersect the J1614-2230 mass line. However, it does not provide any constraint on the possible `exotic' composition of the high-density neutron star matter.

- **Guichon et al., Nucl. Phys. A814 (2008) 66**
  - **result of an on-going collaboration between CSSM & CEA France with Jirina Stone (Oxford)**

Recently Developed Covariant Model Built on the Same Physical Ideas

- Use NJL model (χ‘al symmetry)

- Ensure confinement through proper time regularization
  (following the Tübingen group)

- Self-consistently solve Faddeev Eqn. in mean scalar field

- This solves chiral collapse problem common for NJL
  (because of scalar polarizability again)

- Can test against experiment
  – e.g. spin-dependent EMC effect

- Also apply same model to NM, NQM and SQM – hence n-star

Have also Built a 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**

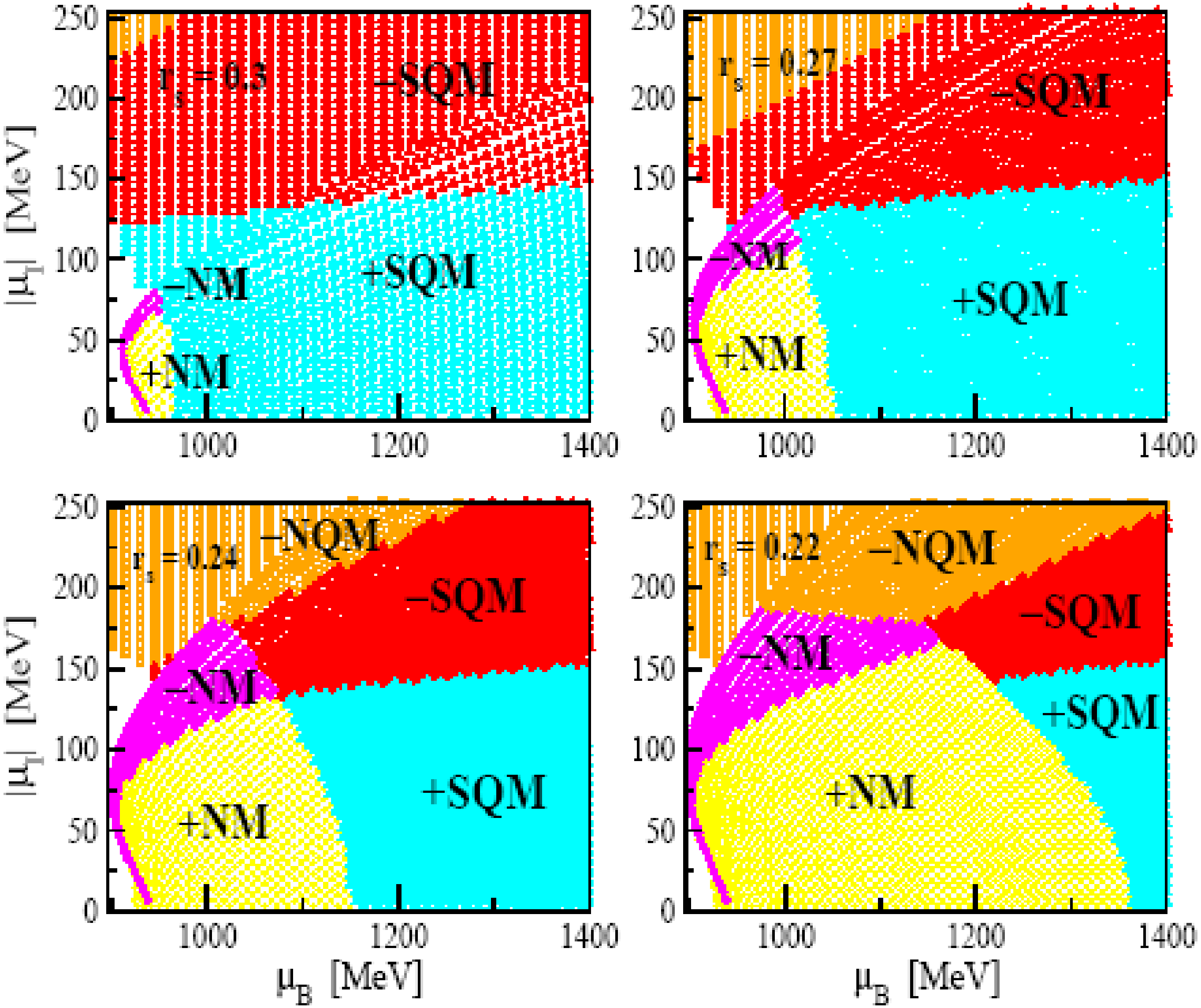
- **Cloet, Bentz, Thomas, Phys. Lett. B642 (2006) 210**

- **Applications to neutron stars – including SQM:**

- **Lawley, Bentz, Thomas, Phys. Lett. B632 (2006) 495**

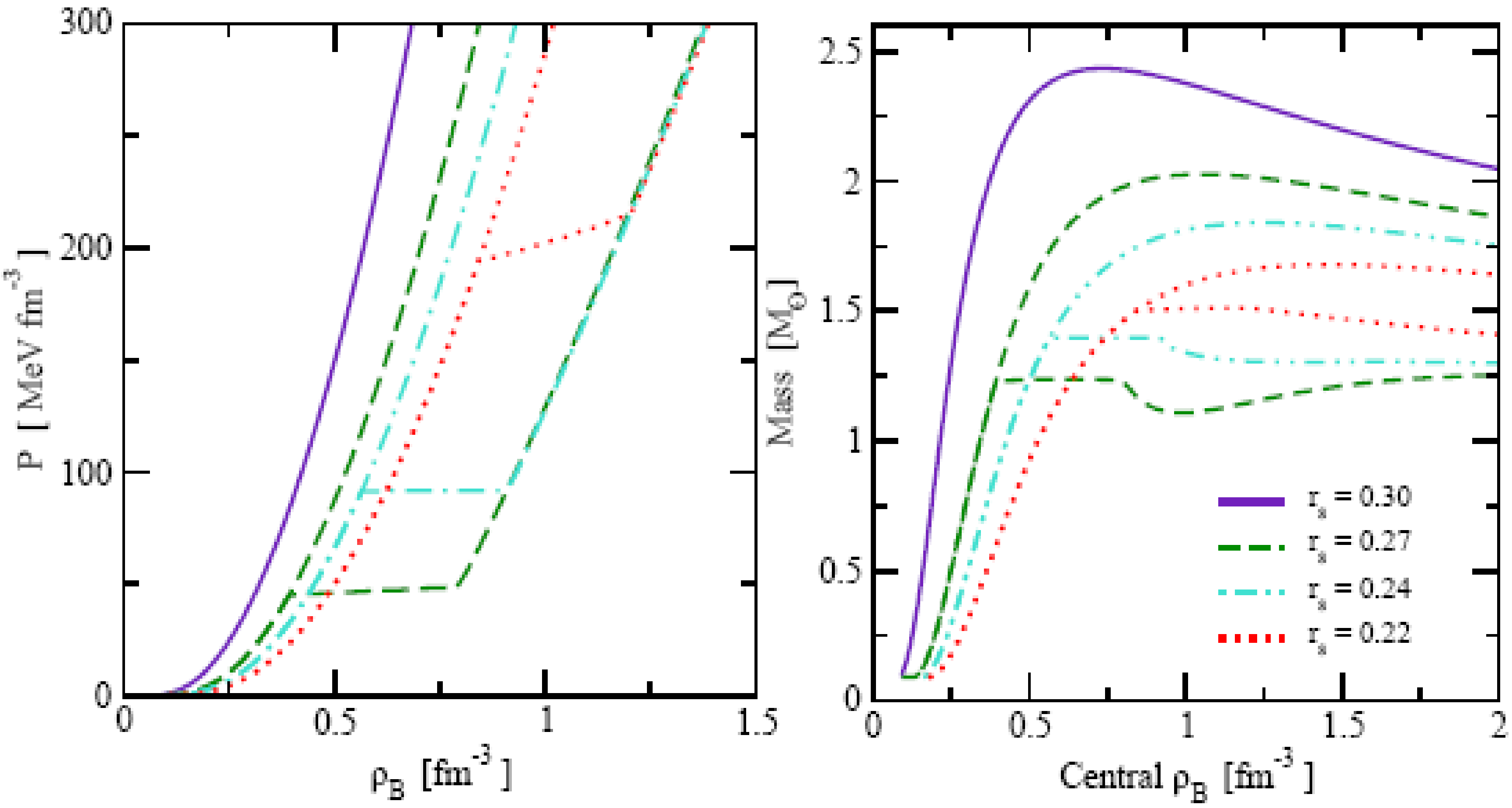
- **Lawley, Bentz, Thomas, J. Phys. G32 (2006) 667**

Phases of Dense Matter : NM to NQM to SQM



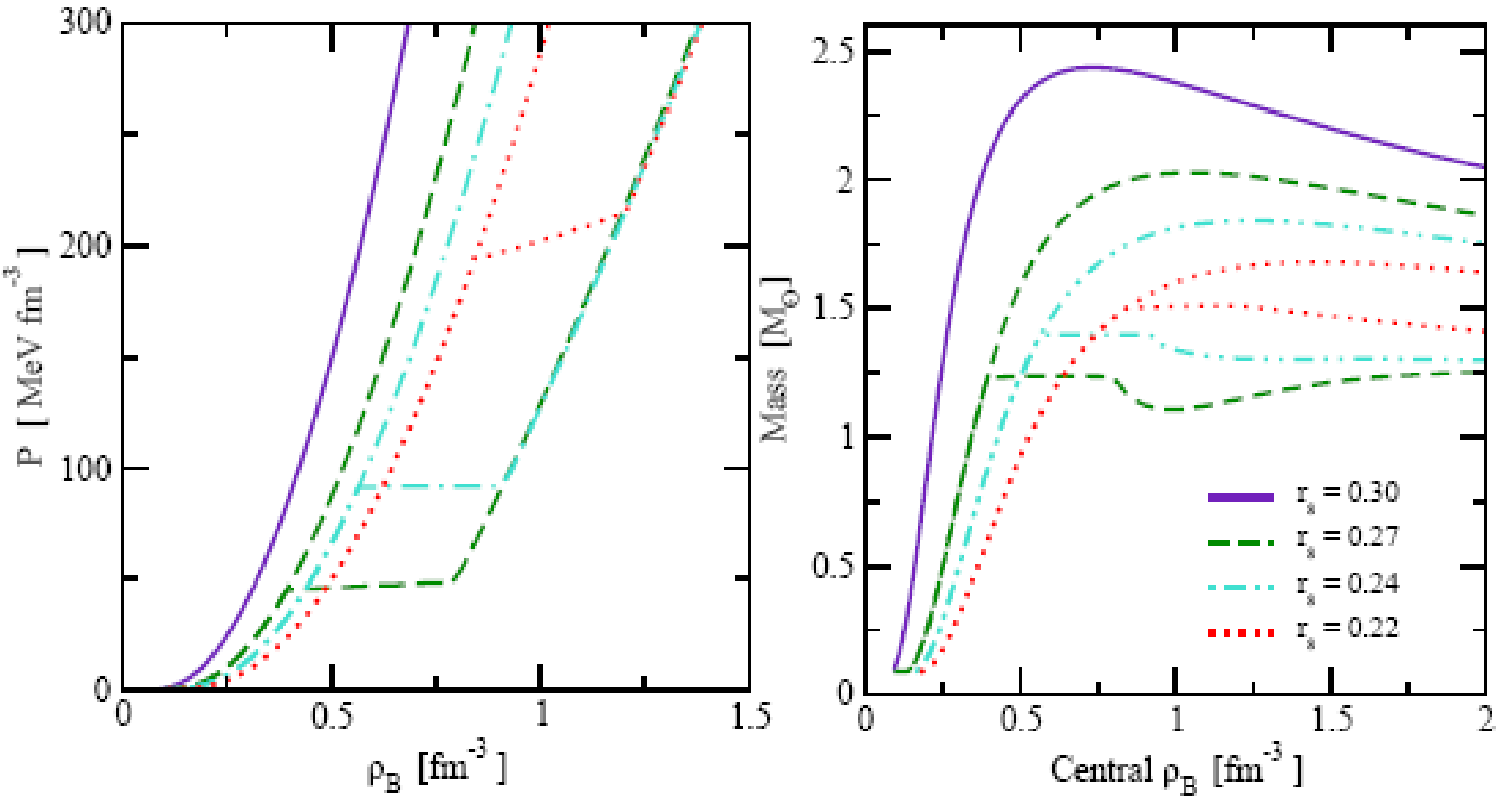
Lawley, Bentz, AWT, nucl-th/0602014 (J Phys G)

EOS of Dense Matter – n Star Properties



Naturally leads to <u>low mass</u>, hybrid n stars with masses ~ independent of the central density

EOS of Dense Matter – n Star Properties



N.B. Hyperons in NM phase would tend to raise transition density a little - still need to include these….

Binding of Other Hadrons

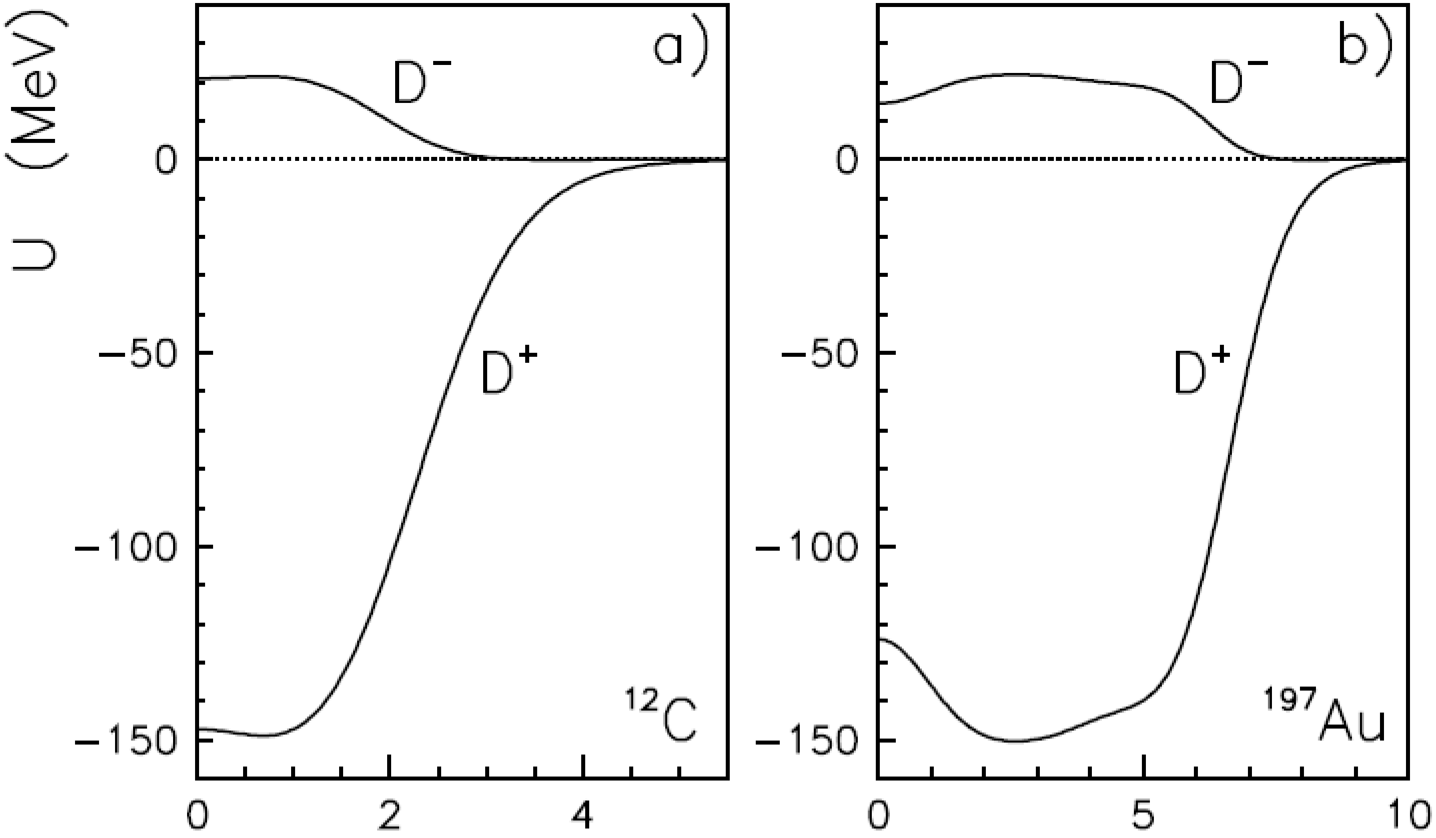
Mesons are Special

- With valence q and anti-q net Lorentz vector force is zero!
- Thus, unlike baryons, we see strong scalar attraction
- Pseudo-scalars are complicated by chiral symmetry (need for many-body effects)
- ρ is very broad
- ω is ideal – expect it to be bound
  − hints from Mainz
- Also naked charm: c qbar (qbar feels attractive scalar AND vector force)

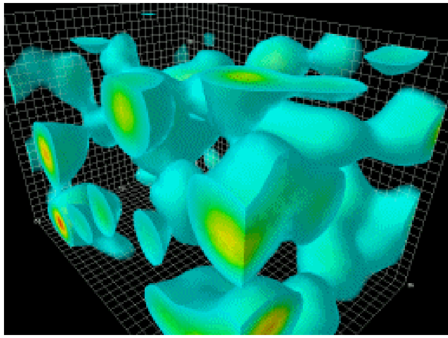
Table 20: Calculated meson-nucleus bound state energies, $E_j = Re(E^*_j - m_j)$, and widtl Γ_j ($j = \omega, \eta, \eta'$), (in MeV) in QMC [163] and those for the ω in QHD, including the effe of σ-ω mixing [180]. The complex eigenenergies are given by, $E^*_j = E_j + m_j - i\Gamma_j/2$. (* n calculated)

		$\Gamma^0_\eta = 0$ $\gamma_\eta = 0.5$	(QMC)	$\Gamma^0_{\eta'} = 0$ (QMC)	$\Gamma^0_\omega = 8.43$ γ_ω=0.2	(MeV) (QMC)
		E_η	Γ_η	$E_{\eta'}$	E_ω	Γ_ω
$^{6}_{j}$He	1s	-10.7	14.5	*	-55.6	24.7
$^{11}_{j}$B	1s	-24.5	22.8	*	-80.8	28.8
$^{26}_{j}$Mg	1s	-38.8	28.5	*	-99.7	31.1
	1p	-17.8	23.1	*	-78.5	29.4
	2s	—	—	*	-42.8	24.8
$^{16}_{j}$O	1s	-32.6	26.7	-41.3	-93.4	30.6
	1p	-7.72	18.3	-22.8	-64.7	27.8
$^{40}_{j}$Ca	1s	-46.0	31.7	-51.8	-111	33.1
	1p	-26.8	26.8	-38.5	-90.8	31.0
	2s	-4.61	17.7	-21.9	-65.5	28.9
$^{90}_{j}$Zr	1s	-52.9	33.2	-56.0	-117	33.4
	1p	-40.0	30.5	-47.7	-105	32.3
	2s	-21.7	26.1	-35.4	-86.4	30.7
$^{208}_{j}$Pb	1s	-56.3	33.2	-57.5	-118	33.1
	1p	-48.3	31.8	-52.6	-111	32.5
	2s	-35.9	29.6	-44.9	-100	31.7

Effective Potentials for D± in nuclei



BUT Calculating Energies is a SMALL Part of the Problem!



- The self-consistent coupling to the scalar field *fundamentally modifies the structure of the hadron*
- Hence form factors and structure functions change in-medium
- At quark level it's the lower components of the valence quark Dirac wave functions that are most effected
- N.B. calculation relies on Born-Oppenheimer approximation: motion must be slow enough for structure to adjust to the local mean scalar field!

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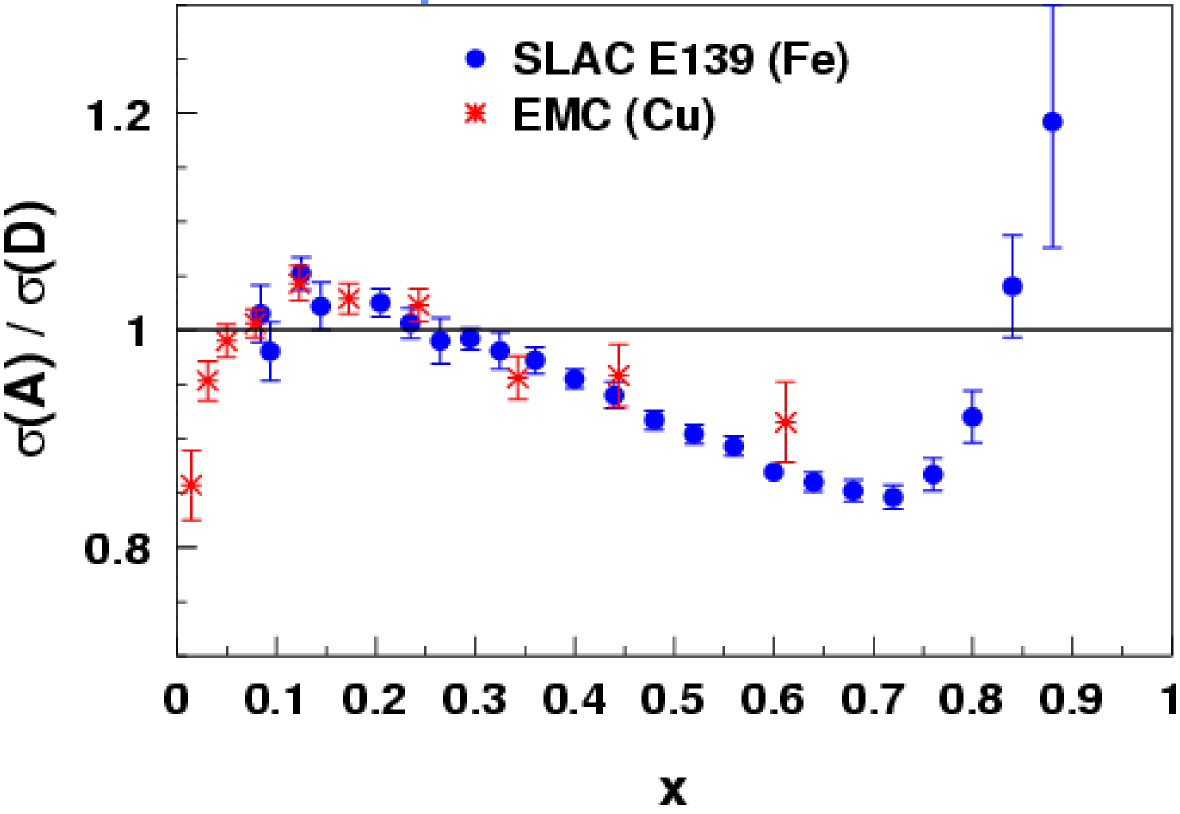
The EMC Effect: Nuclear PDFs

- 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)

Recent Calculations for Finite Nuclei

Spin dependent EMC effect TWICE as large as unpolarized

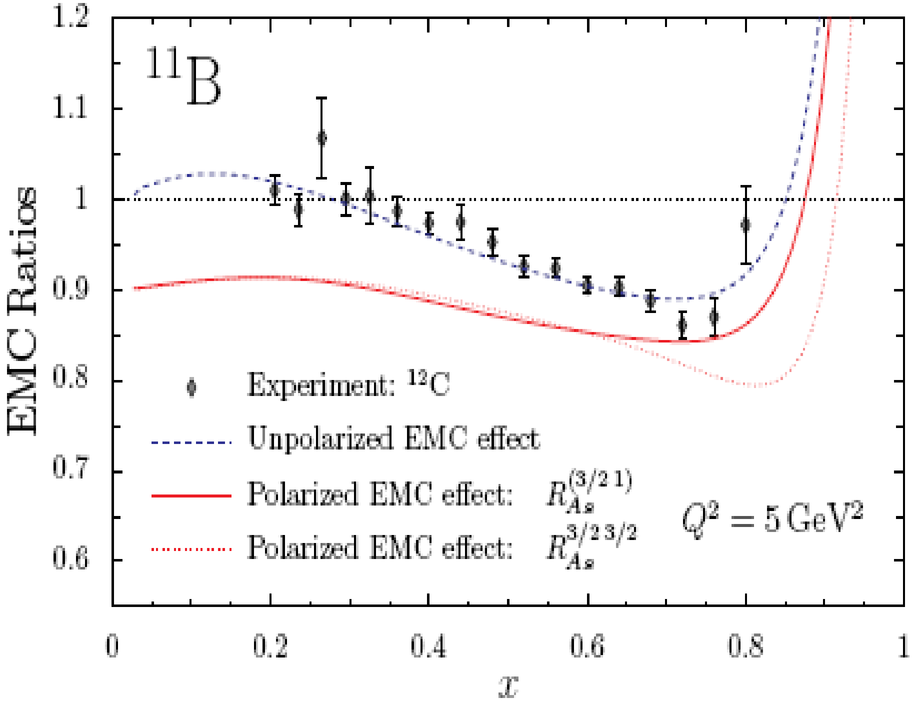


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

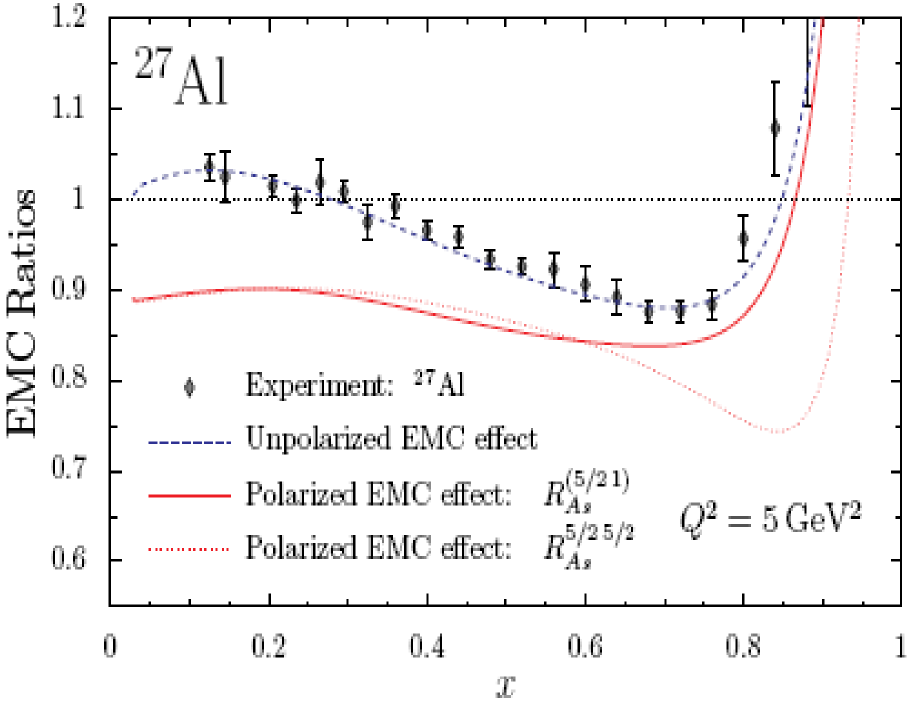


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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

Summary-1

- For dense matter relativity matters

- 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

- Change of intrinsic structure “scalar polarizability”

- This is a natural source of three-body force
  clear physical interpretation

- Resulting, equivalent effective force is remarkably close to successful Skyrme forces

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Summary -2

- Derived, density-dependent effective force gives results better than 95% of the phenomenological Skyrme forces
  - BUT its derived with MANY less parameters

- **Encourage community to use it…**

- Same model also yields effective, density dependent Λ N, Σ N, Ξ N forces (not yet published)

- Availability of realistic, density dependent Hyperon-N forces is essential for $\rho > 2\text{-}3\ \rho_0$

- Already important results for n stars

Special Mentions……