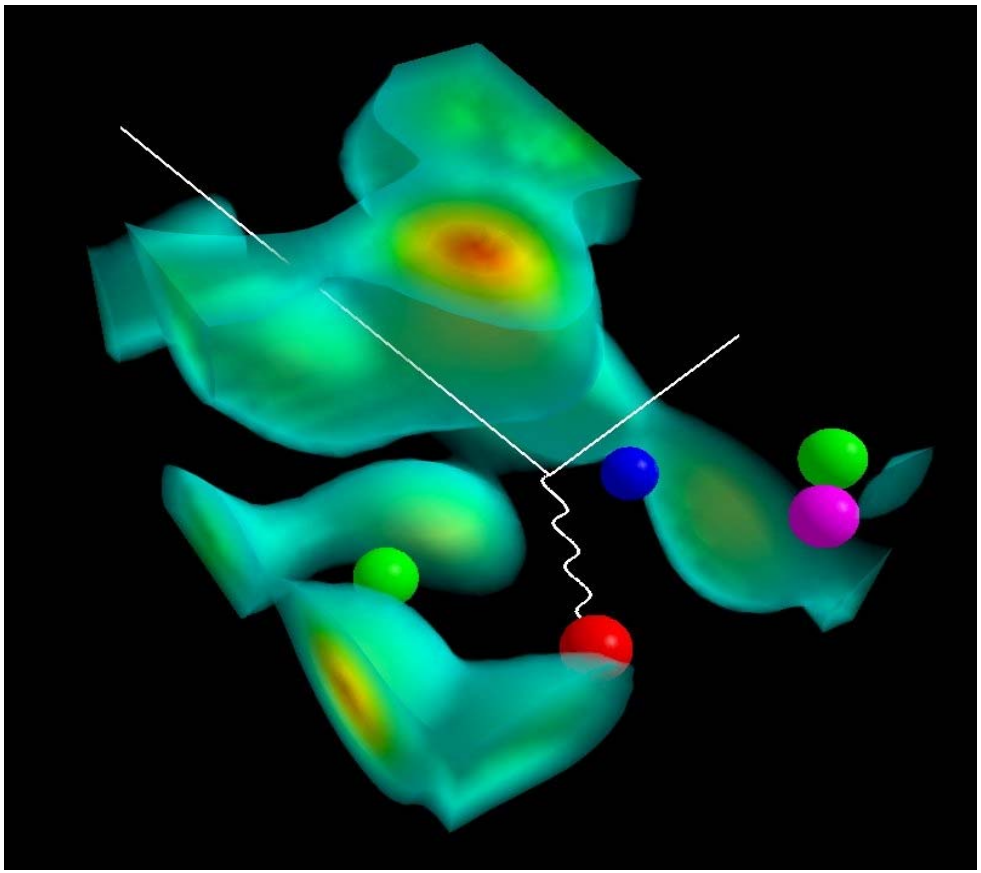
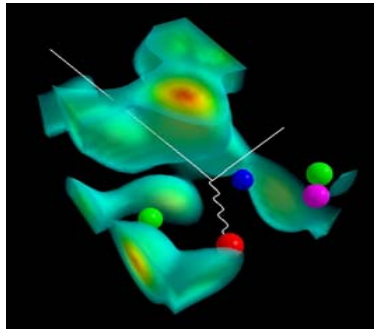
Realistic Density Dependent Forces Derived from the Quark Level



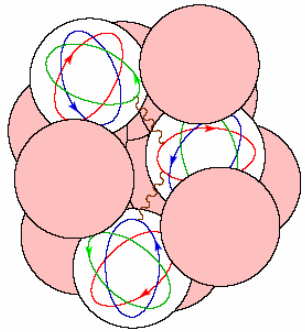
Anthony W. Thomas

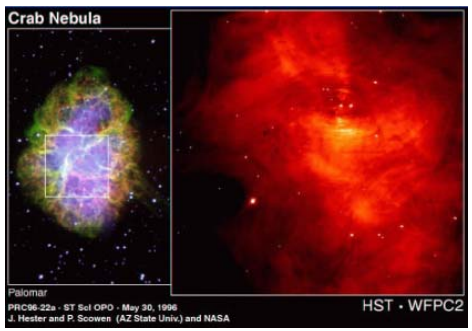
INPC 2007 : 4th June 2007

Λ, Ξ, ω, D, J/Ψ …… in nuclear matter



QCD & hadron structure

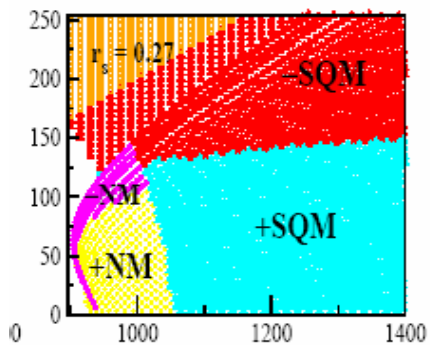




n star

∞ nuclear matter

Effective density dependent NN (and N Λ, N Ξ …) forces



quark matter

Finite nuclei
Hypernuclei

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!**

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

- **Classical mean-field implementation is Walecka model**

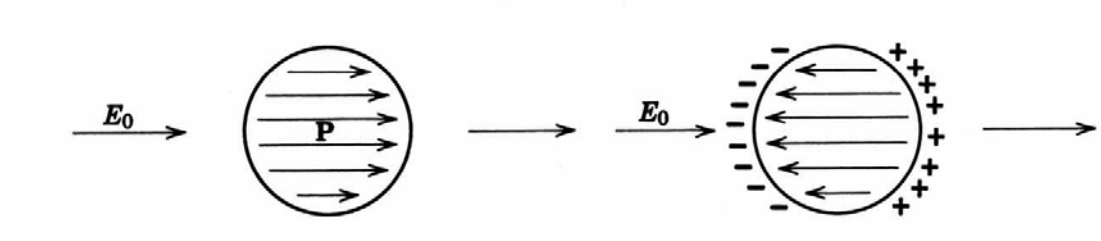
  → $m_N^* / m_N \sim 0.5$ at ρ_0

This is a huge applied scalar 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



Adds <u>second order term</u> in the energy as a function of E (proportional to electric 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 ≡ scalar polarizability

d ≈ 0.22 R in original QMC (MIT bag)

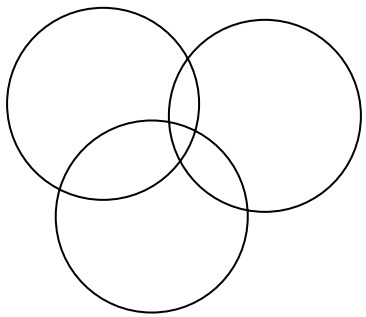
Indeed, in nuclear matter at mean-field level (e.g. QMC), this is the ONLY place the response of the internal structure of the nucleon enters.

Effect of 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 is natural existence of many-body forces:**



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

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

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

Great Start: What's Next

Remove small σ field approximation

- **Derive density-dependent forms**
- **Add the pion**
- **Derive 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**

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 $< \sigma > = 0$

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

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

~ 4% ~ 1%

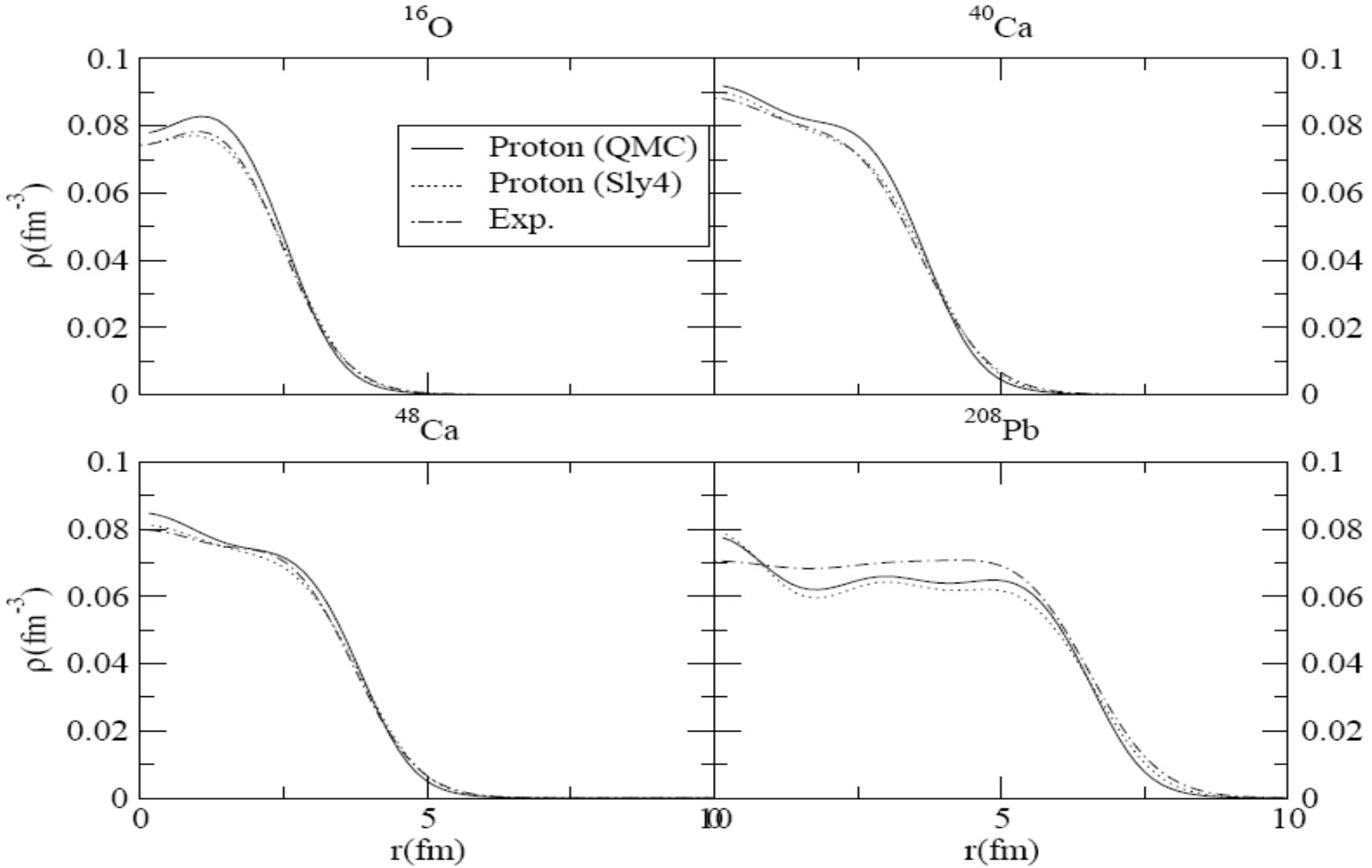
- Where analytic form of (e.g. $H_0 + H_3$) piece of energy functional derived from QMC is:

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

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

○ highlights scalar polarizability

Excellent Agreement with Sly4 for Charge Distributions



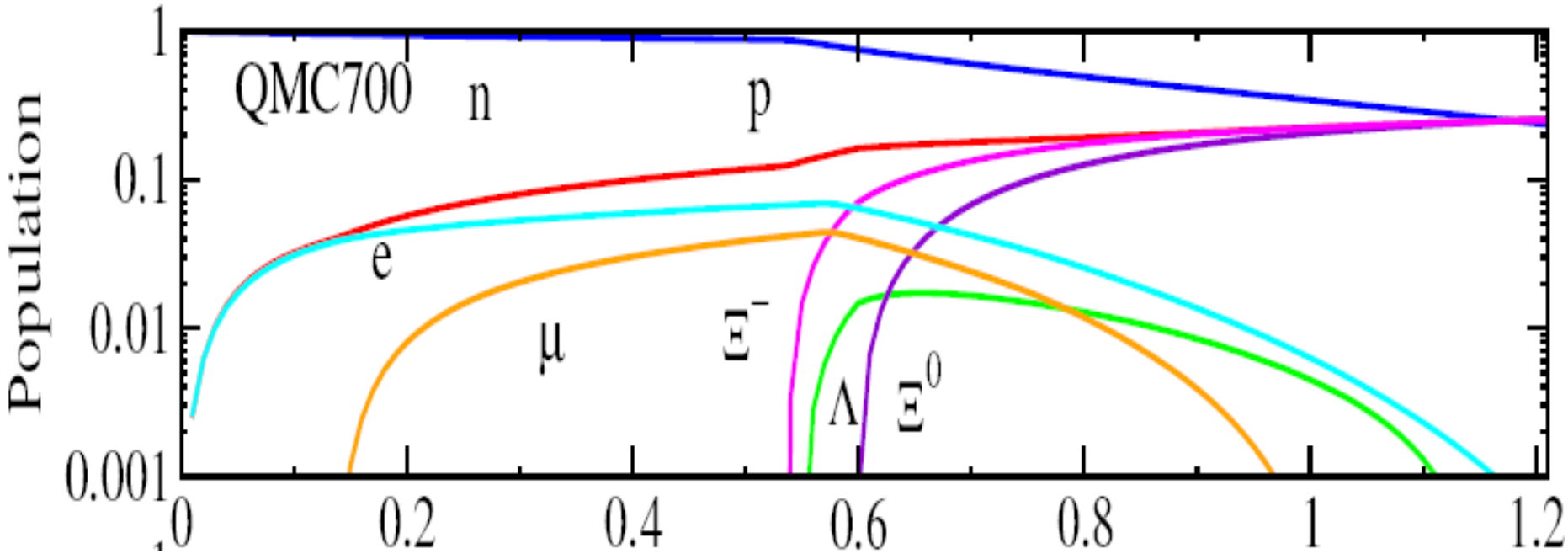
Spin-Orbit Splitting

	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

Consequences for Neutron Star

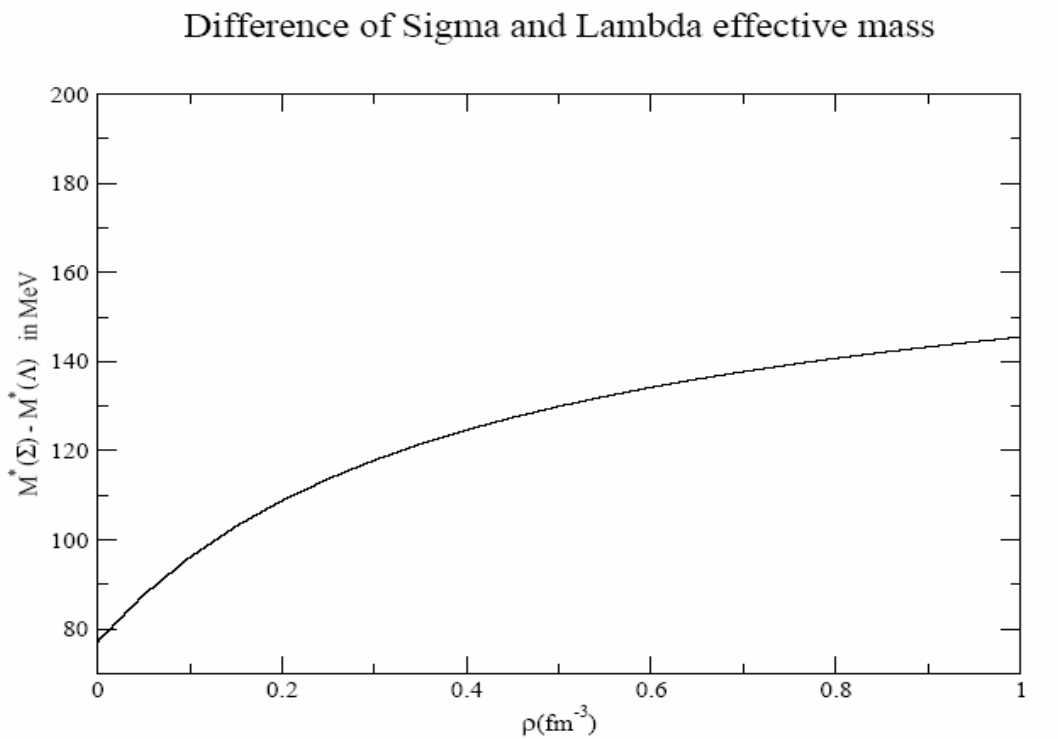
New QMC model, fully relativistic, Hartree-Fock treatment



Stone, Guichon, Matevosyan, Thomas, nucl-th/0611030

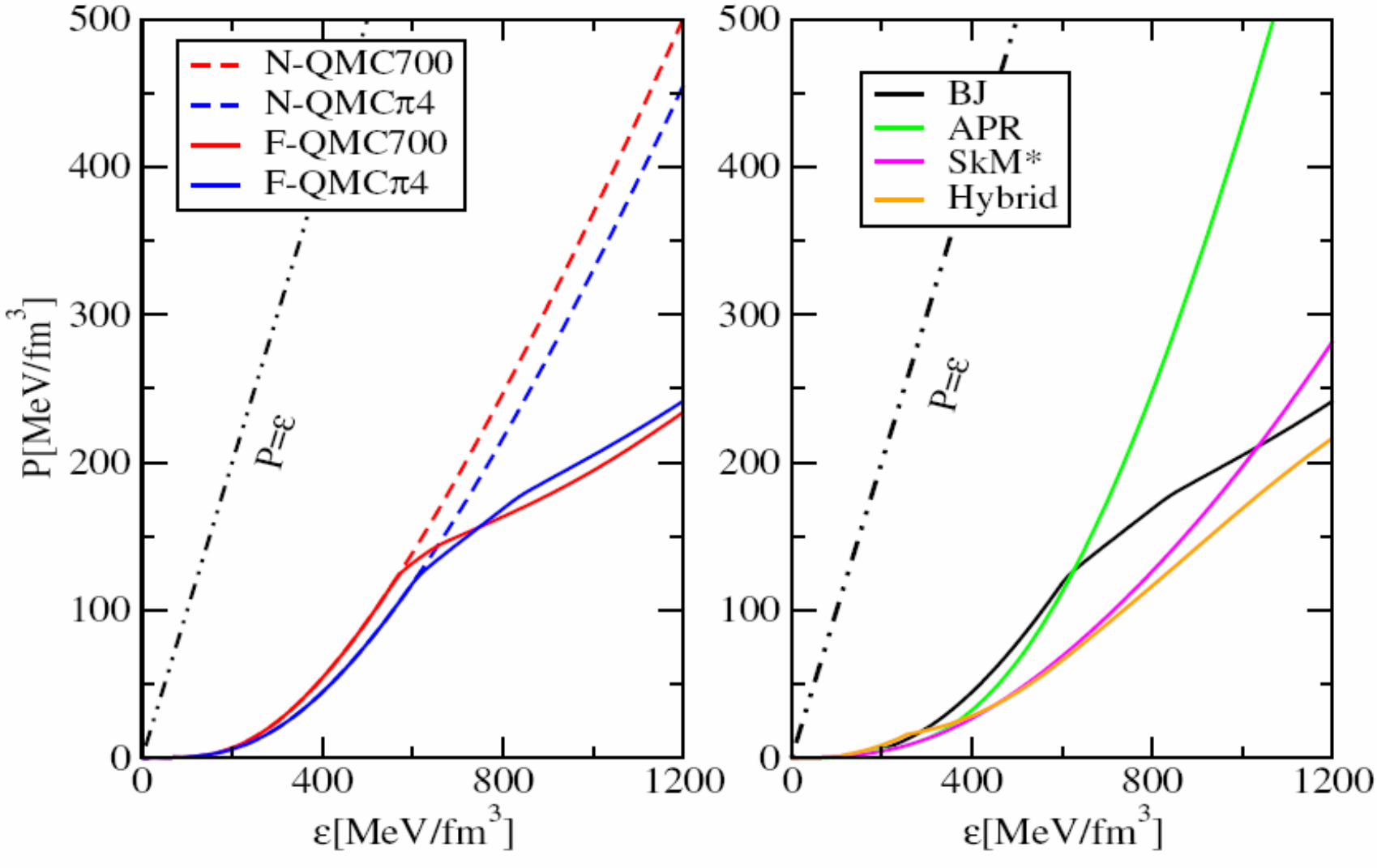
Explanation: Latest QMC Includes Medium Modification of Hyperfine Interaction

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



Guichon, Stone, Thomas, Tsushima: to appear

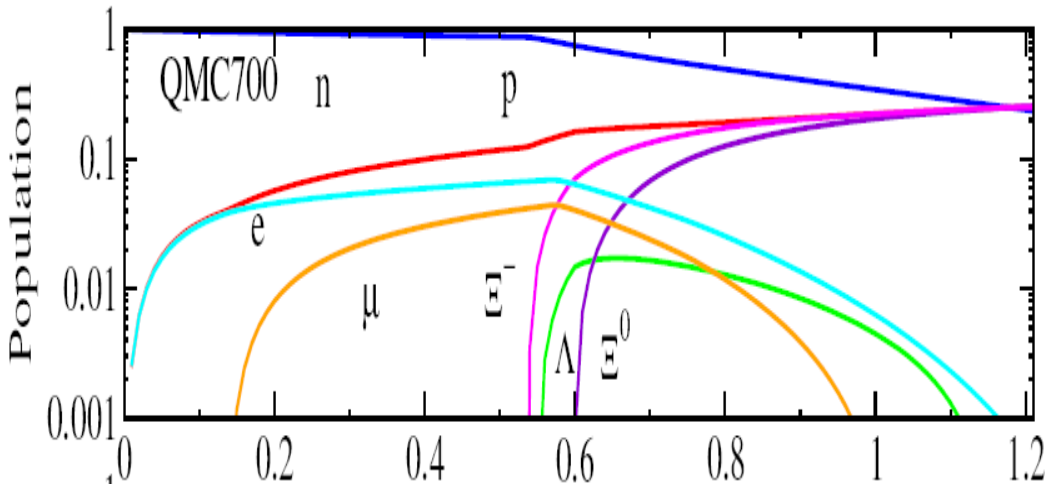
Effect of Hyperons on the Nuclear EoS

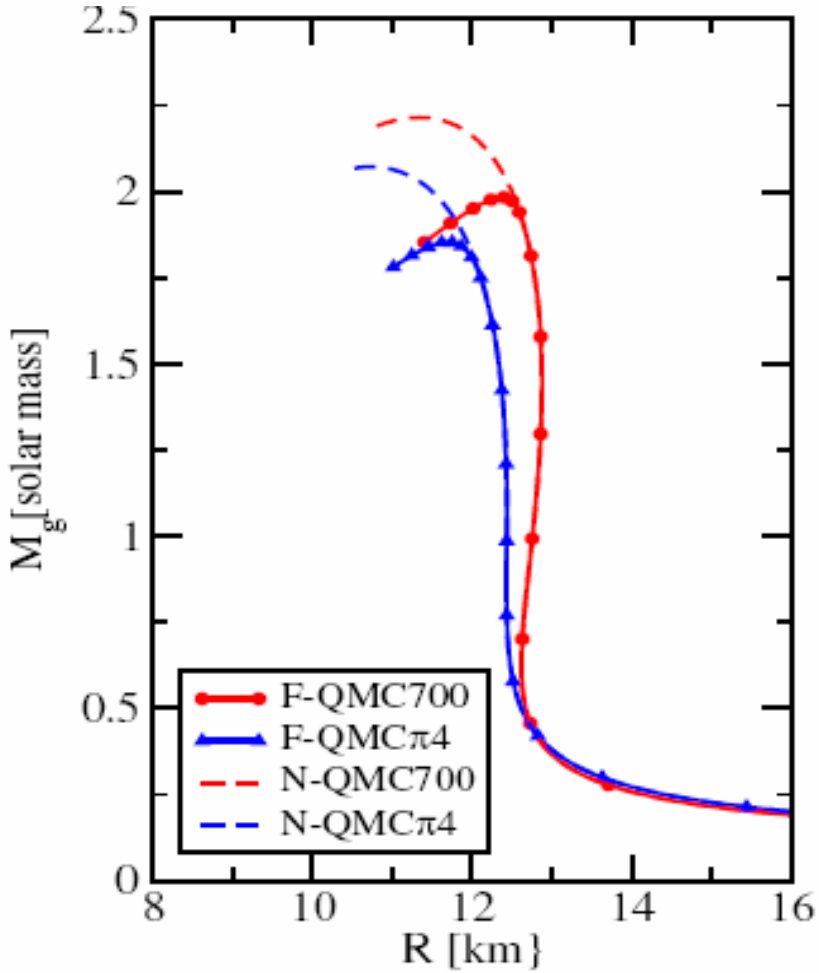


Stone, Guichon, Matevosyan, Thomas, nucl-th/0611030

Consequences for Neutron Star

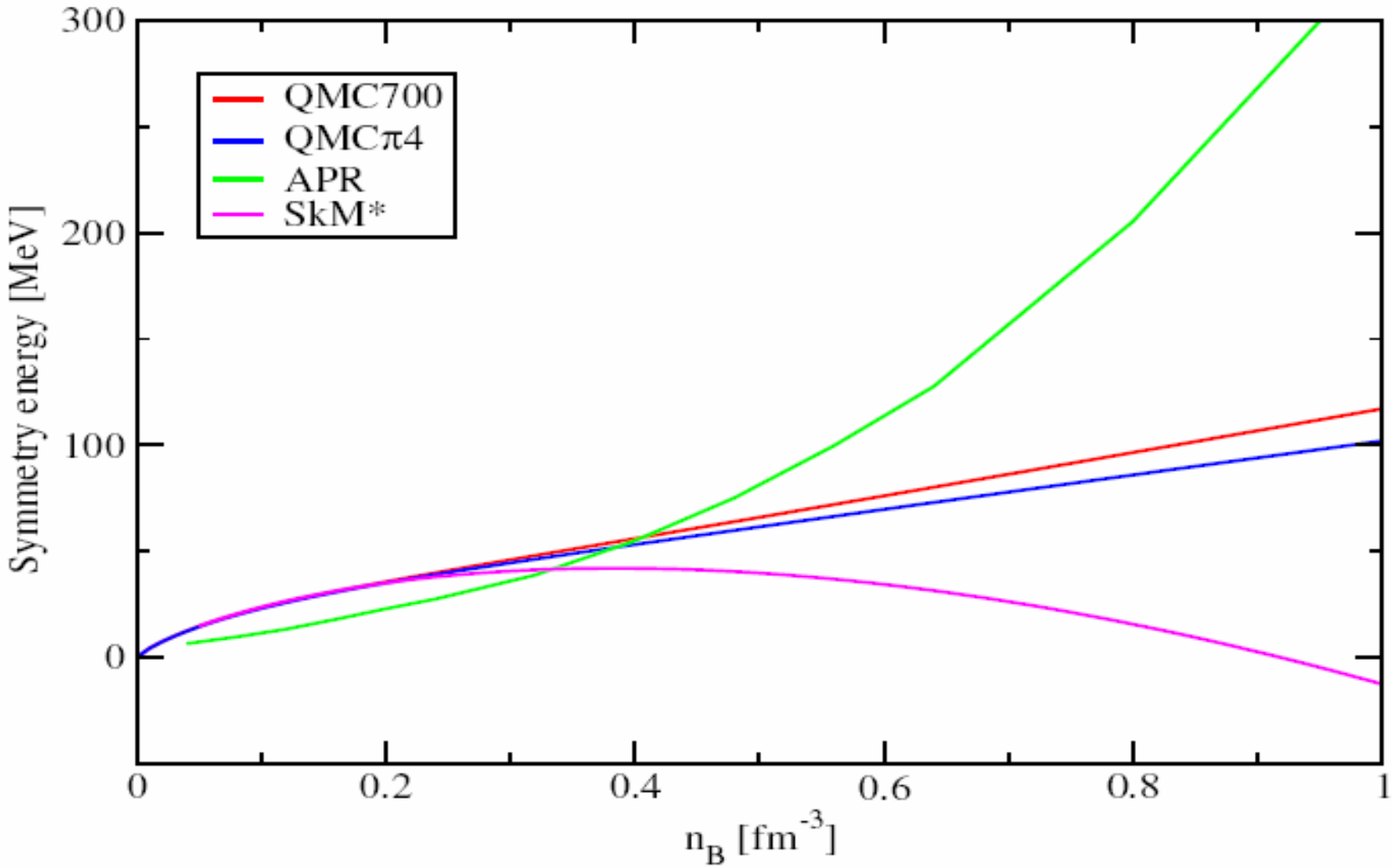
New QMC model, fully relativistic, Hartree-Fock treatment





Stone, Guichon, Matevosyan, Thomas, nucl-th/0611030

Traditional Models Differ Significantly at 2-3 ρ_0



Summary-1

- Intermediate attraction in NN force is STRONG scalar
- This modifies the intrinsic structure of the bound nucleon $\Rightarrow$ **profound change in shell model**
  what occupies shell model states are NOT free nucleons
- Change of intrinsic structure $\equiv$ "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

Summary -2

- Derived, density-dependent effective force gives results remarkably close to SkM and Sly4 for finite nuclei – 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 $\rho > 2\text{-}3\ \rho_0$

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 (hep-ph/0506314)