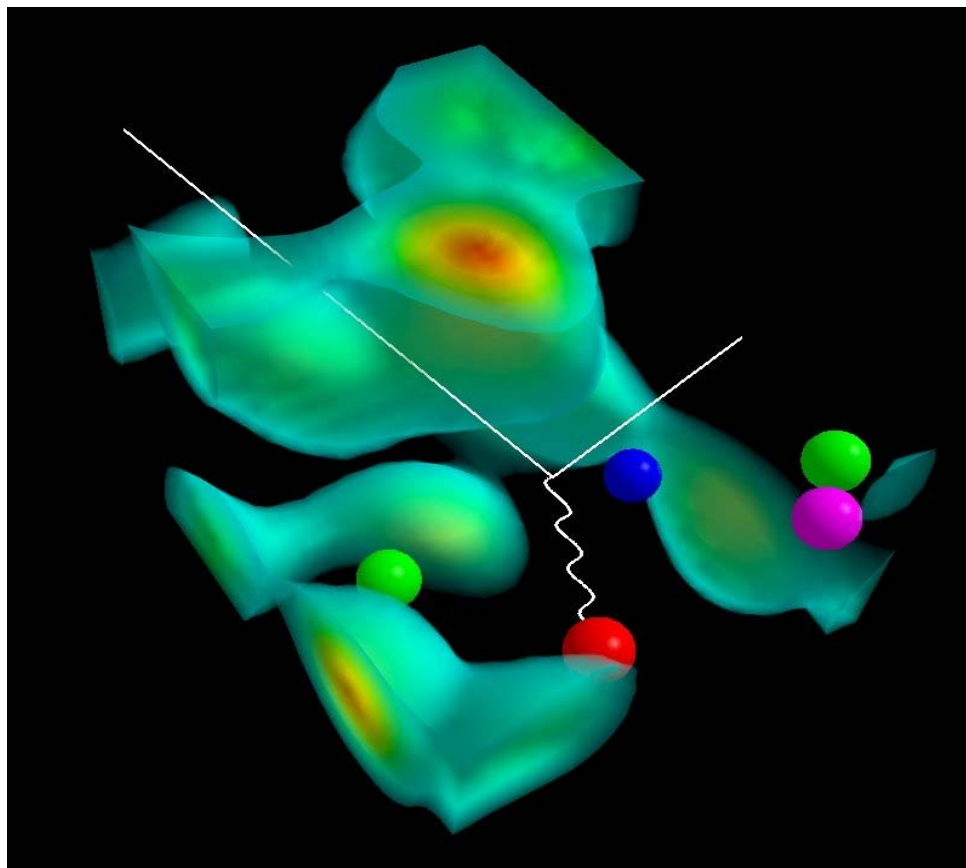


# Origin of the Nuclear EOS in Hadronic Physics and QCD



**Anthony W. Thomas**

**Workshop on SRC**

**in Honor of Kim Egiyan: JLab October 20<sup>th</sup>, 2006**

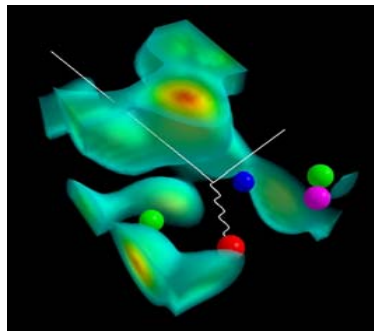
Thomas Jefferson National Accelerator Facility



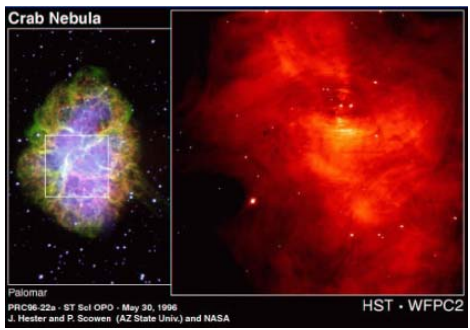
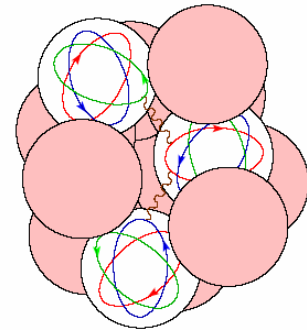
Operated by Jefferson Science Associates for the U.S. Department of Energy



$\Lambda, \Xi, \omega, D, J/\Psi$  ..... in nuclear matter



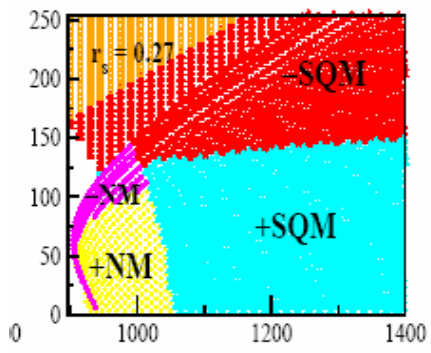
QCD & hadron structure



n star

$\infty$  nuclear matter

Effective NN (and N  $\Lambda$ , N  $\Xi$  ...) 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. (in press) hep-ph/0506314

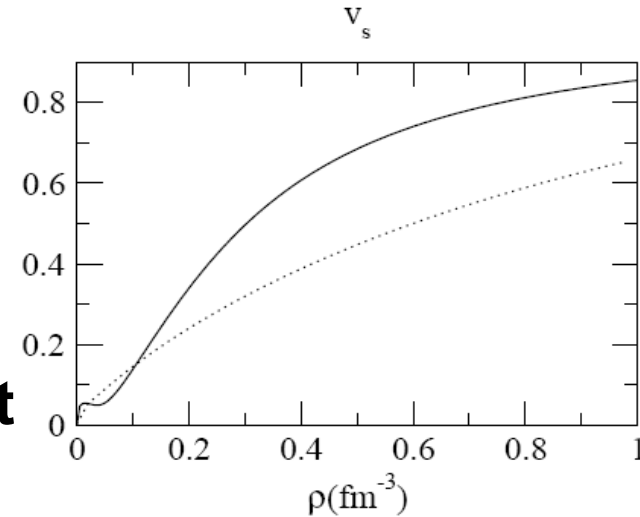
# Model Independent Features of NN Force

- Intermediate Range attraction is **Lorentz scalar-isoscalar** (since 70's, dispersion relations, Paris potential...)
- **Lorentz scalar force is strong!**
- 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  $\rho_0$

# Relativity Matters in Dense Matter

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

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



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

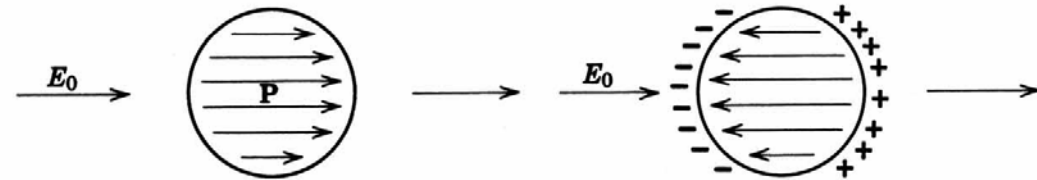
-  $\pi$  : but easily added and irrelevant in MFA

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

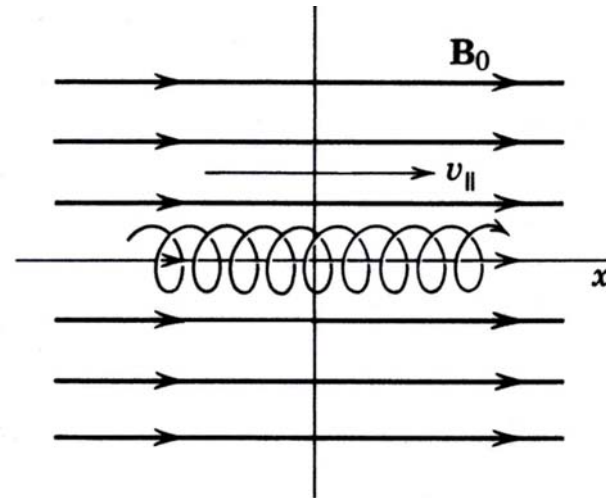
# What happens if we put an atom in a strong electric field?

Jackson  $\Rightarrow$

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

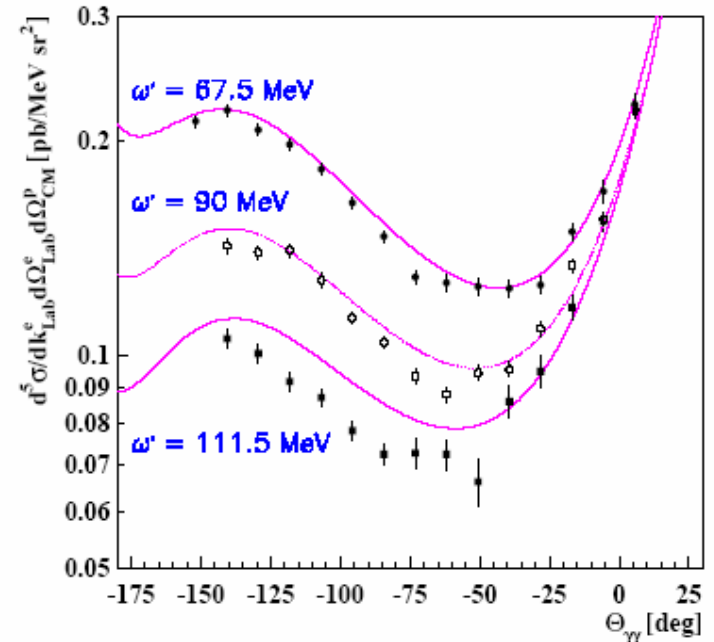
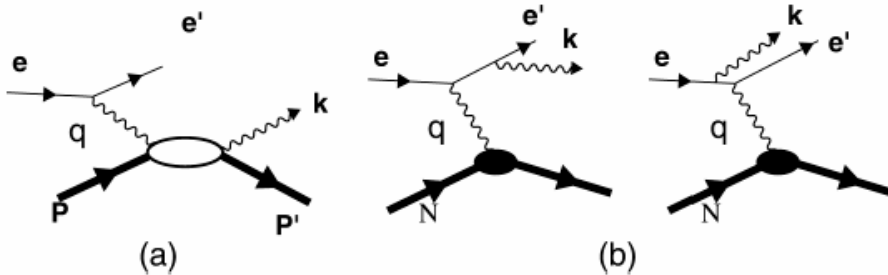
e.g. Compton scattering:

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

$$\alpha_E^P = (12.1 \pm 1.3) \cdot 10^{-4} \text{ fm}^3,$$

$$\beta_M^P = (2.1 \mp 1.3) \cdot 10^{-4} \text{ fm}^3.$$

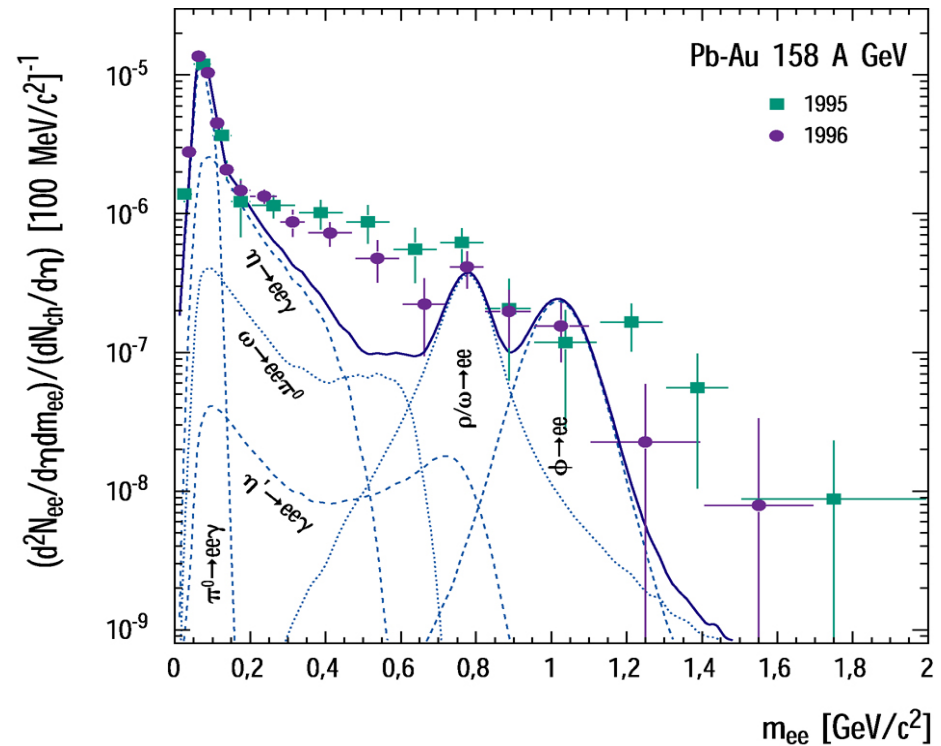
Also Virtual Compton Scattering  $\Rightarrow$  GPs



# 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  $\Rightarrow$  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...

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

Non-linear dependence  $\equiv$  scalar polarizability  
 $d \approx 0.22 R$  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  $\sigma$   
changes:

$$\int B a g d\vec{r} \bar{\psi}(\vec{r}) \psi(\vec{r})$$

**SELF-CONSISTENCY**

and hence mean scalar field changes...

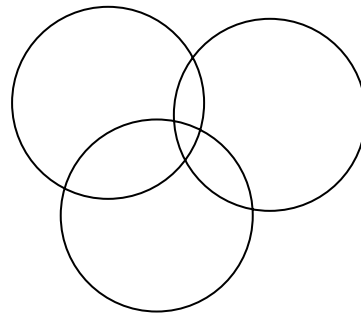
and hence quark wave function changes....

**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)**

# 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:



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

# 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

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 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!

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

P.A.M. Guichon<sup>1</sup>, H.H. Matevosyan<sup>2,3</sup>, N. Sandulescu<sup>1,4,5</sup> and A.W. Thomas<sup>2</sup>

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

**No longer need to expand around  $\langle \sigma \rangle = 0$**

$m_\sigma$ (MeV)	$t_0$ (fm <sup>2</sup> )	$t_1$ (fm <sup>4</sup> )	$t_2$ (fm <sup>4</sup> )	$t_3$ (fm <sup>5/2</sup> )	$x_0$	$W_0$ (fm <sup>4</sup> )	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  $m_\sigma$

**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

- 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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○ 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

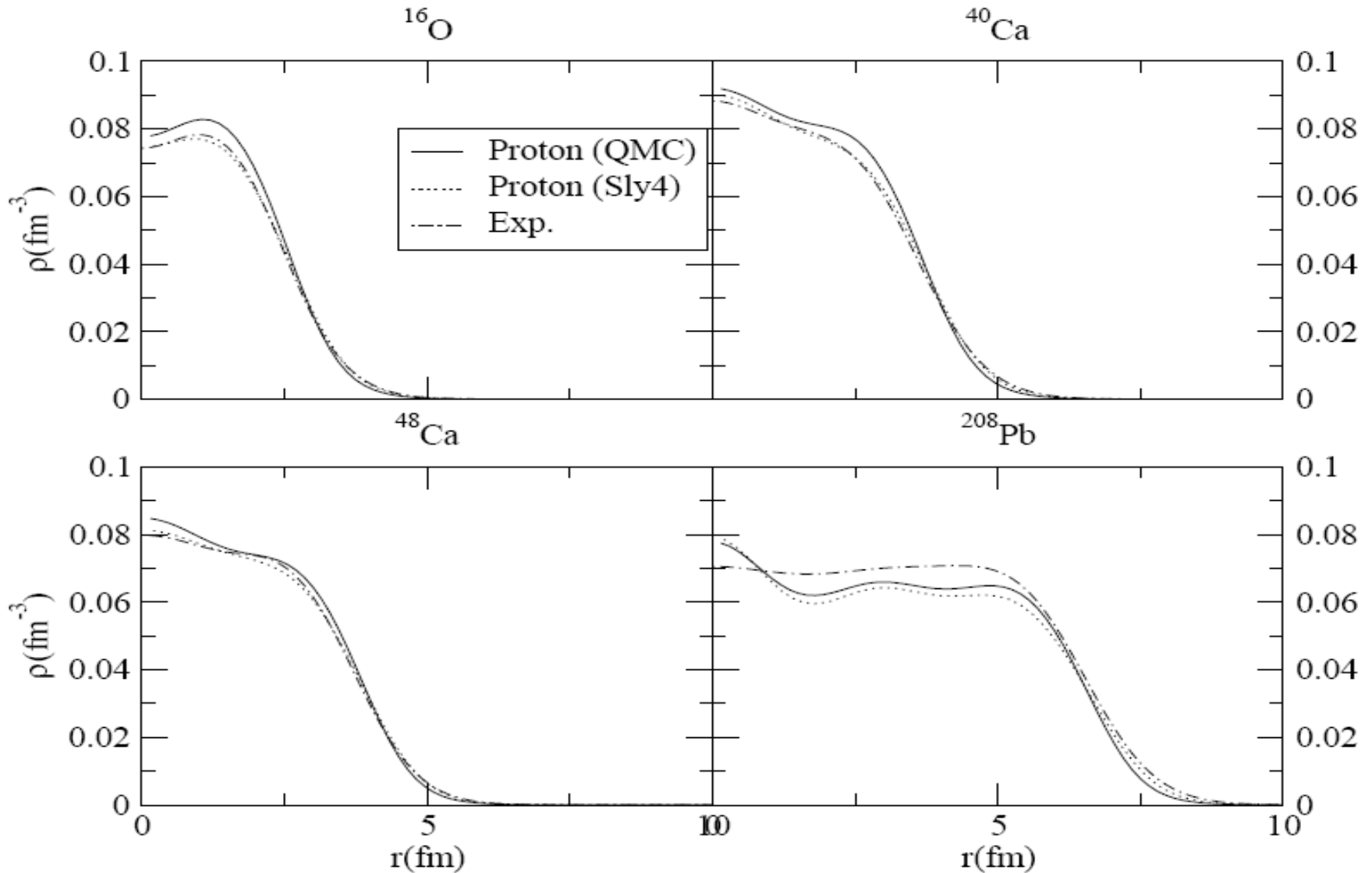
- In comparison with the SkM force:

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

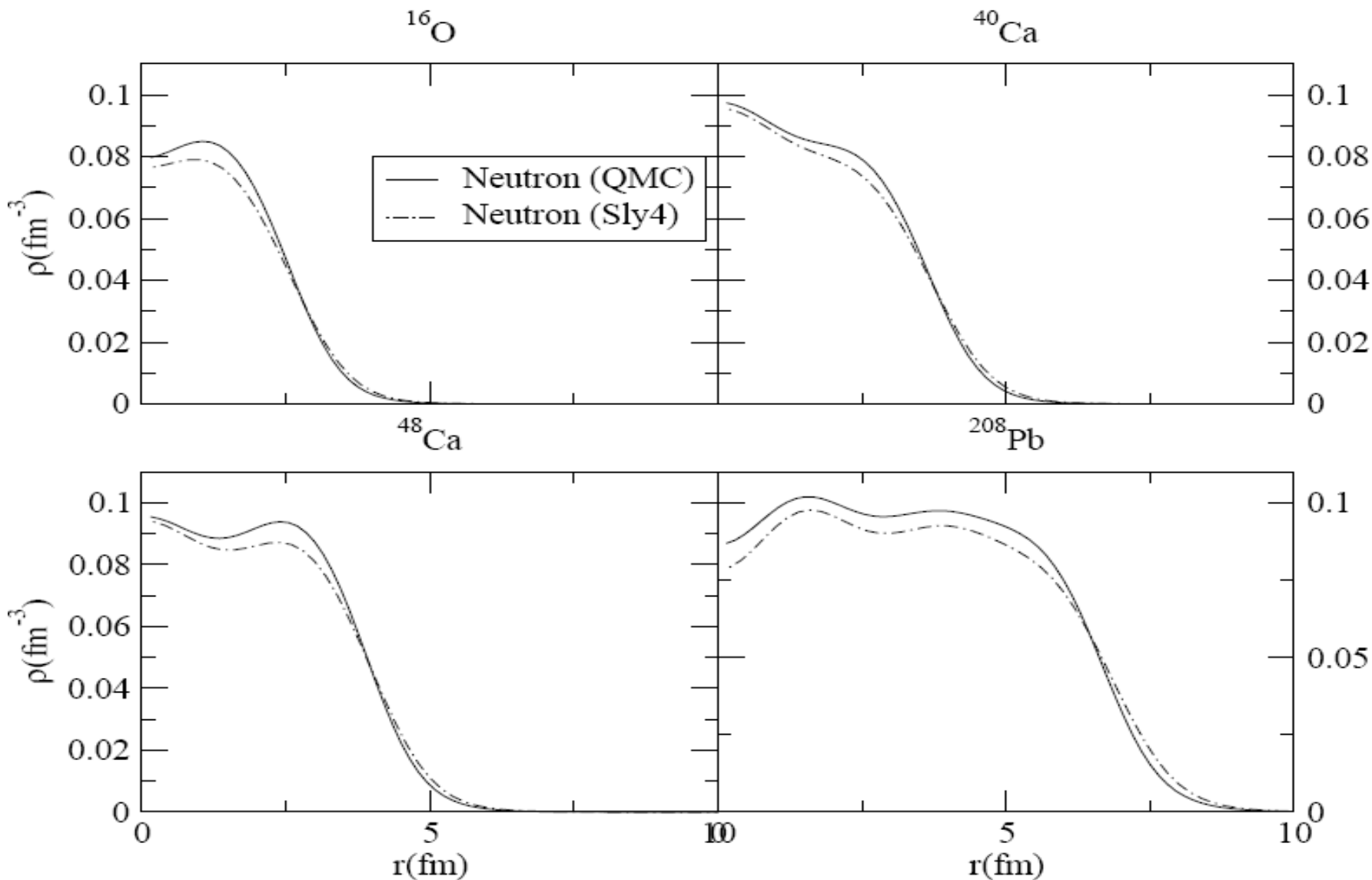
and full energy functional in both cases is:

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

# Excellent Agreement with Sly4 for Charge Distributions



# Neutron Densities vs Sly4 – also excellent



# Spin-Orbit Splitting

	Neutrons (Expt)	Neutrons (QMC)	Protons (Expt)	Protons (QMC)
<sup>16</sup> O 1p <sub>1/2</sub> -1p <sub>3/2</sub>	6.10	6.01	6.3	5.9
<sup>40</sup> Ca 1d <sub>3/2</sub> -1d <sub>5/2</sub>	6.15	6.41	6.0	6.2
<sup>48</sup> Ca 1d <sub>3/2</sub> -1d <sub>5/2</sub>	6.05 (Sly4)	5.64	6.06 (Sly4)	5.59
<sup>208</sup> Pb 2d <sub>3/2</sub> -2d <sub>5/2</sub>	2.15 (Sly4)	2.04	1.87 (Sly4)	1.74

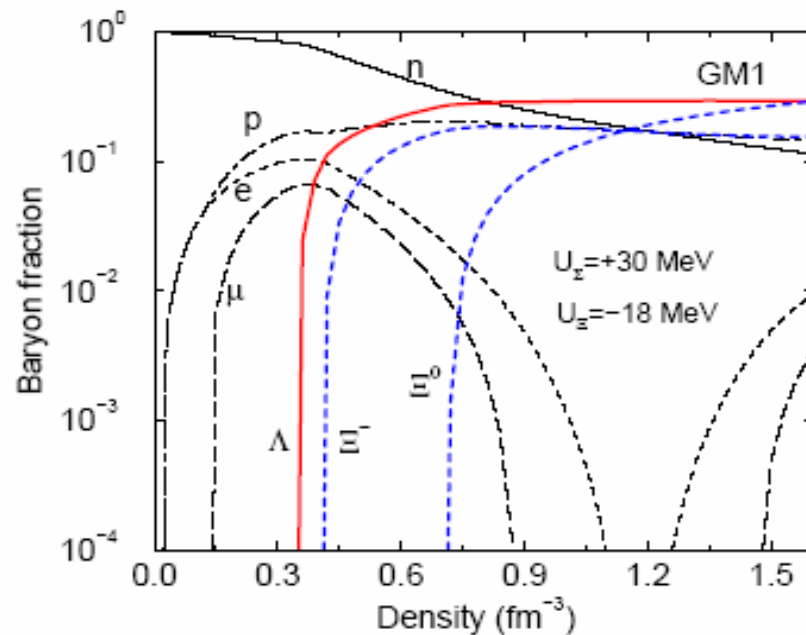
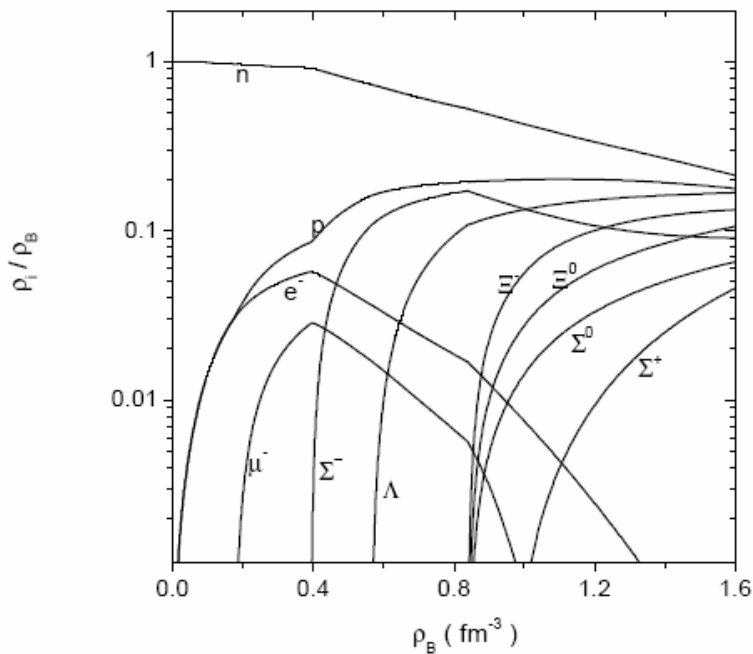
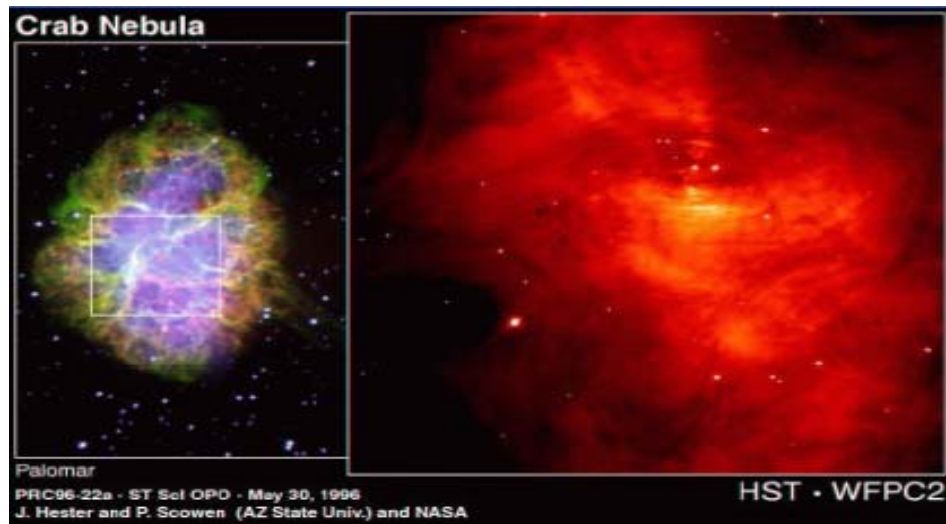
Agreement generally very satisfactory – NO parameter adjusted to fit

# Great Start: What's Next

Remove small  $\sigma$  field approximation

- Derive density-dependent forms
- Add the pion
- Derive  $\Lambda N$ ,  $\Sigma N$ ,  $\Lambda \Lambda \dots$  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 enter at just 2-3  $\rho_0$
- Hence need effective  $\Sigma$ -N and  $\Lambda$ -N forces in this density region!
- Hypernuclear data is important input (J-PARC, FAIR, JLab)



# Finite Hypernuclei with New QMC

	$^{16}_{\Lambda}\text{O}$ (Expt.)	$^{17}_{\Lambda}\text{O}$	$^{17}_{\Sigma^{-}}\text{O}$	$^{17}_{\Sigma^0}\text{O}$	$^{17}_{\Sigma^{+}}\text{O}$	$^{17}_{\Xi^{-}}\text{O}$	$^{17}_{\Xi^0}\text{O}$
$1s_{1/2}$	-12.5	-16.4	-6.3	-1.4	—	-11.2	-5.2
$1p_{3/2}$		-6.4	—	—	—	-3.7	—
$1p_{1/2}$	-2.5 (1p)	-6.2	—	—	—	-3.9	—
	$^{40}_{\Lambda}\text{Ca}$ (Expt.)	$^{41}_{\Lambda}\text{Ca}$	$^{41}_{\Sigma^{-}}\text{Ca}$	$^{41}_{\Sigma^0}\text{Ca}$	$^{41}_{\Sigma^{+}}\text{Ca}$	$^{41}_{\Xi^{-}}\text{Ca}$	$^{41}_{\Xi^0}\text{Ca}$
$1s_{1/2}$	-20.0	-21.1	-2.2	-2.3	—	-17.9	-8.7
$1p_{3/2}$		-13.8	-7.4	—	—	-12.0	-3.7
$1p_{1/2}$	-12.0 (1p)	-13.7	-6.6	—	—	-12.1	-3.9
$1d_{5/2}$		-5.7	-1.1	—	—	-5.8	—
$2s_{1/2}$		-3.3	-0.9	—	—	-5.3	—
$1d_{3/2}$		-5.5	-1.0	—	—	-6.1	—

- Relativistic Hartree only:  $\Lambda$  still well described
- $\Sigma$  unbound or barely bound – big improvement

Guichon, Matevosyan, Thomas, Tsushima, to appear



Thomas Jefferson National Accelerator Facility

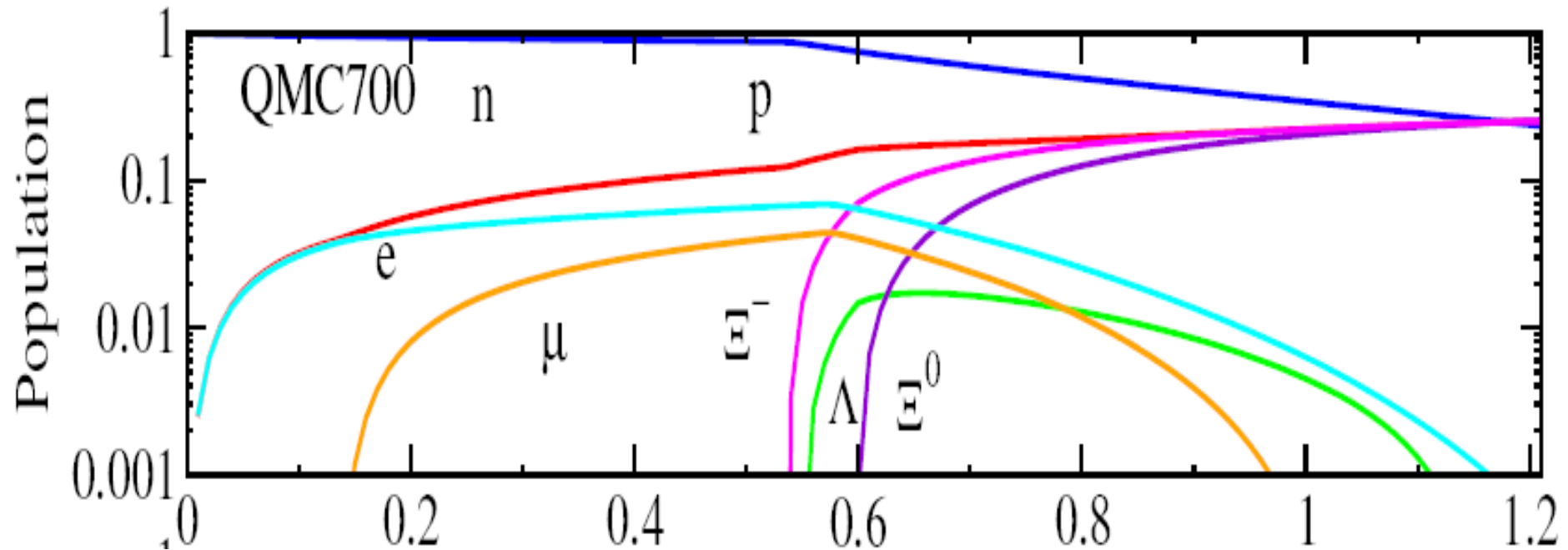
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U.S. DEPARTMENT OF ENERGY

# Consequences for Neutron Star

New QMC model, fully relativistic, Hartree-Fock treatment



Stone, Guichon, Matevosyan, Thomas, to appear



# Recently Developed Covariant Model Built on the Same Physical Ideas

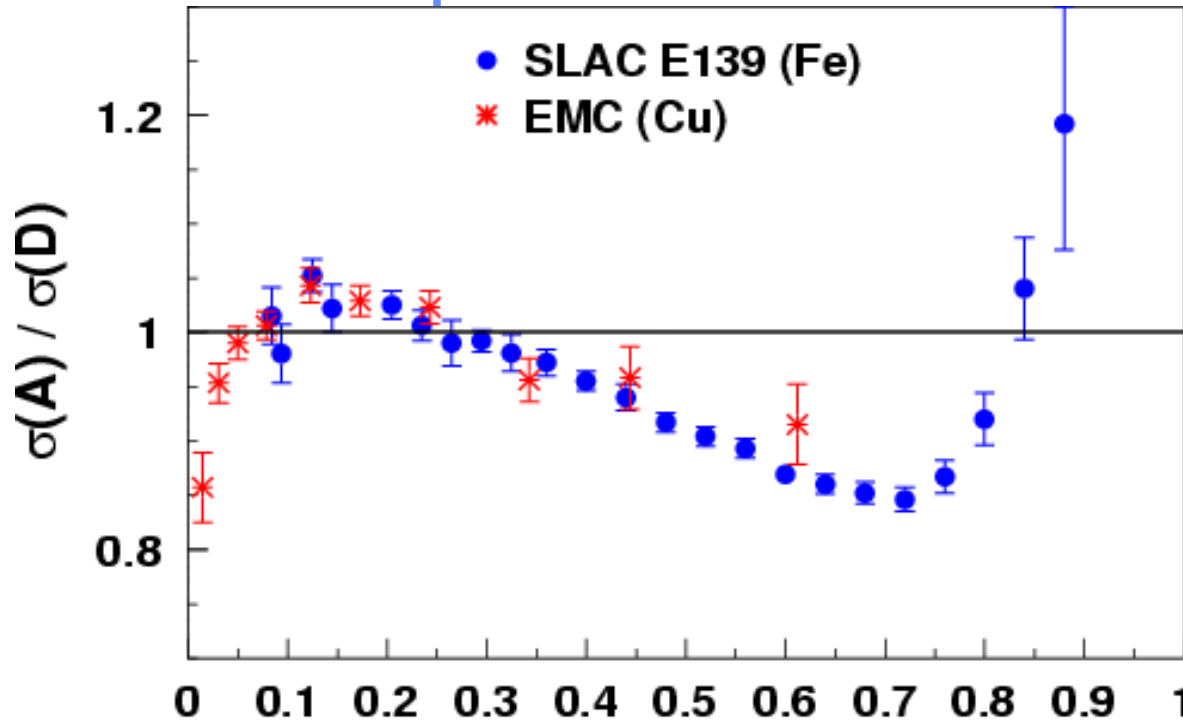
- Use NJL model ( $\chi$ 'al symmetry)
- Ensure **confinement** through proper time regularization (following the Tübingen group)
- Self-consistently solve Faddeev Eqn. in mean scalar field
- This **solves chiral collapse problem** common for NJL (because of scalar polarizability again)
- Can **test against experiment**
  - e.g. spin-dependent EMC effect
- Also apply **same model to NM, NQM and SQM** – hence **n-star**

# Covariant Quark Model for Nuclear Structure

- **Basic Model:**
- **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**
- **Applications to neutron stars – including SQM:**
- **Lawley, Bentz, Thomas, Phys. Lett. B632 (2006) 495**
- **Lawley, Bentz, Thomas, J. Phys. G32 (2006) 667**

# 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?

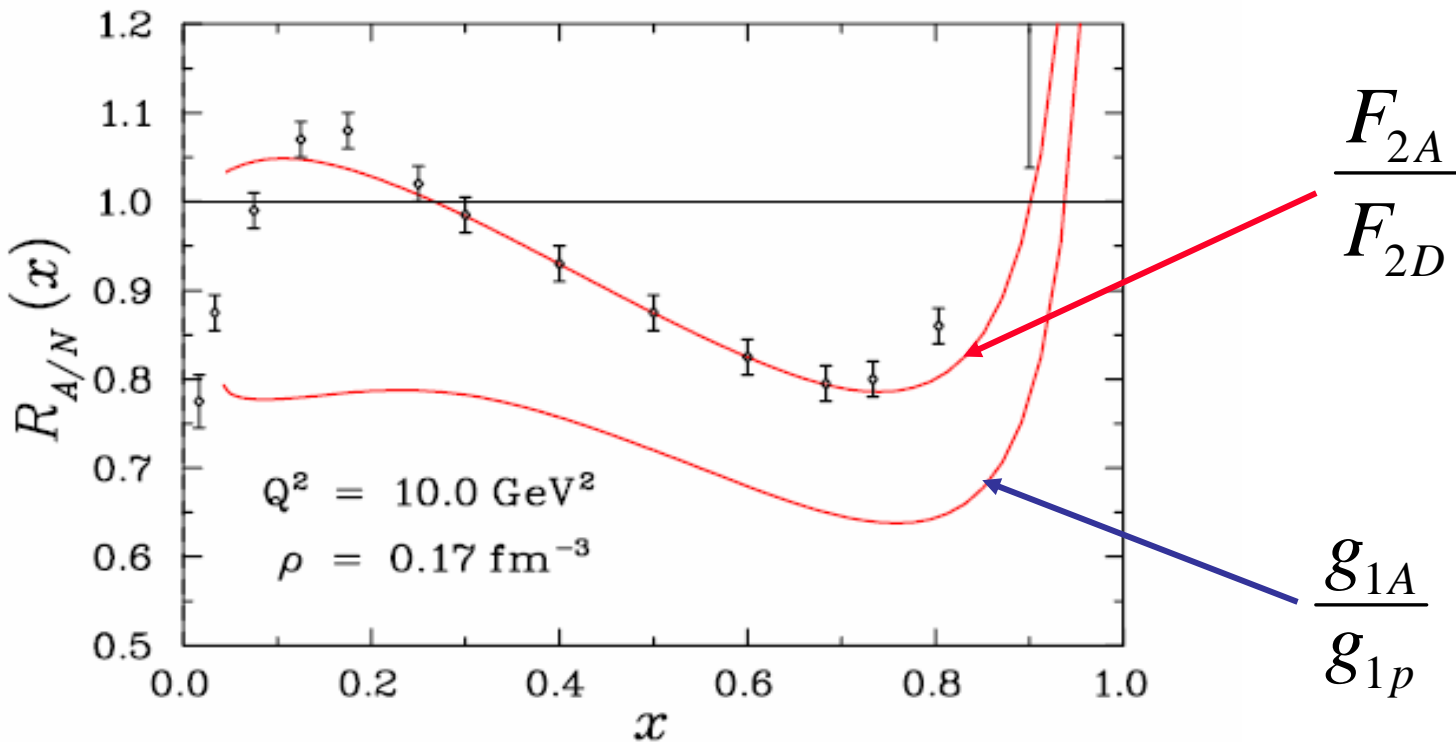


J. Ashman *et al.*, *Z. Phys. C57*, 211 (1993)

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

# $g_1(A)$ – “Polarized EMC Effect”

- Calculations described here  $\Rightarrow$  larger effect for polarized structure than unpolarized: mean scalar field modifies lower components of the confined quark’s Dirac wave function
- Spin-dependent parton distribution functions for nuclei unmeasured



( Cloet, Bentz, AWT, PRL 95 (2005) 0502302 )

# Recent Calculations for Finite Nuclei

Spin dependent EMC effect TWICE as large as unpolarized

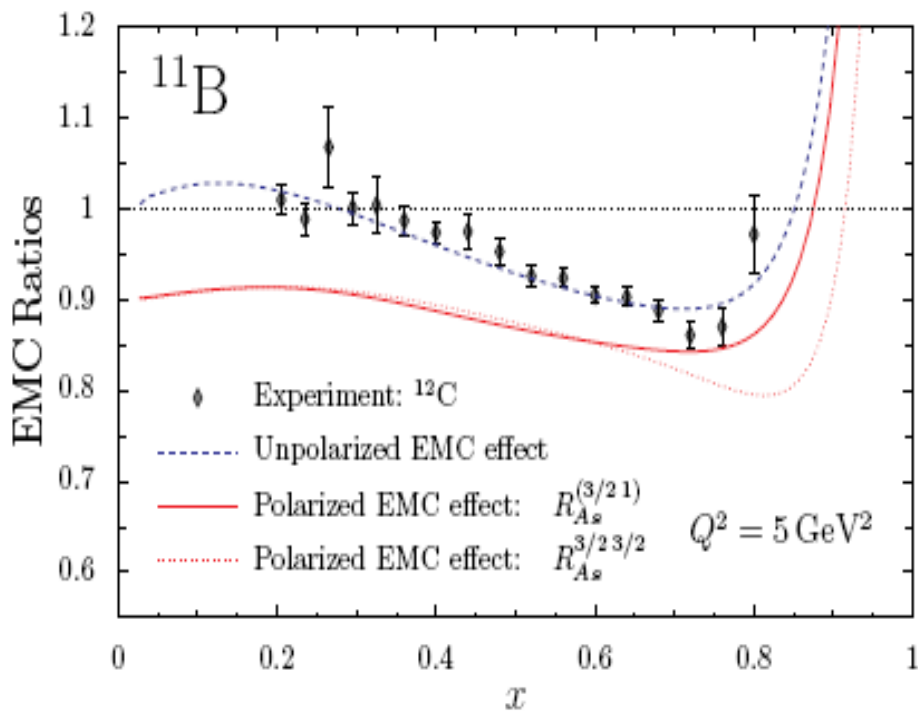


FIG. 7: The EMC and polarized EMC effect in  $^{11}\text{B}$ . The empirical data is from Ref. [31].

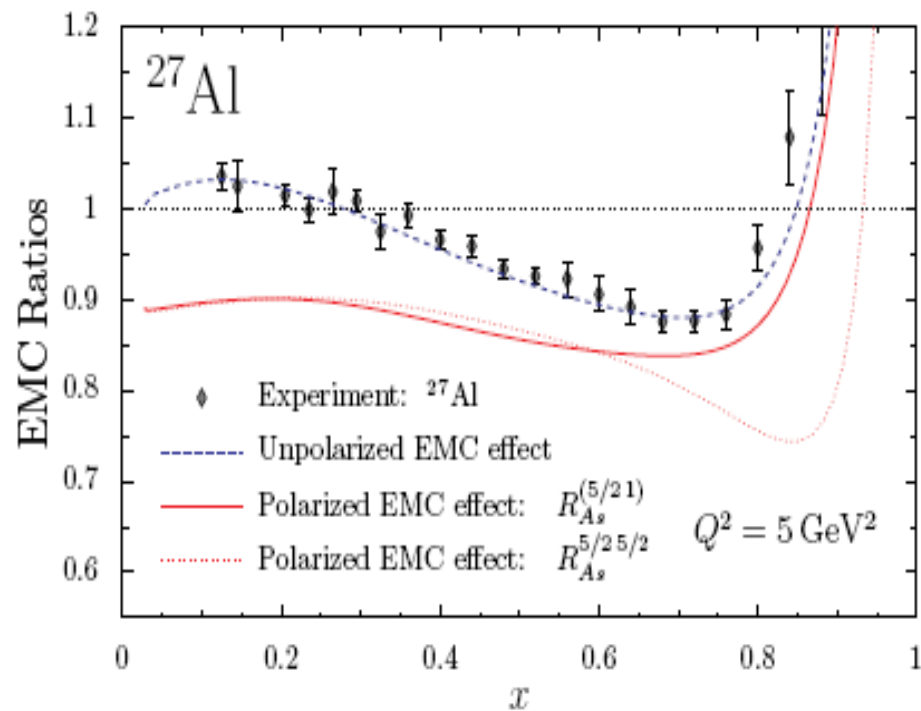
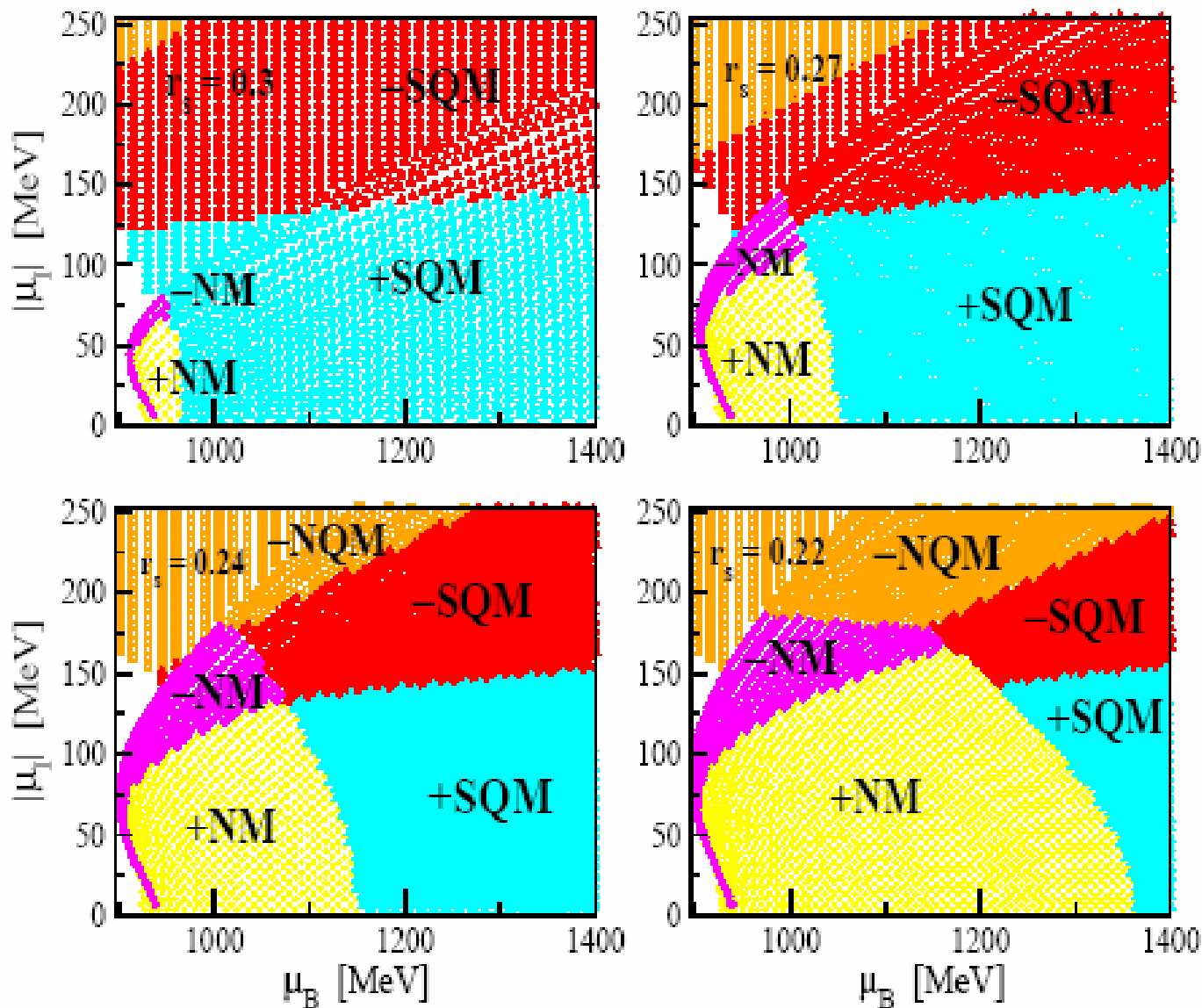


FIG. 9: The EMC and polarized EMC effect in  $^{27}\text{Al}$ . The empirical data is from Ref. [31].

Cloet, Bentz, Thomas, Phys. Lett., to appear 2006 (nucl-th/0605061)

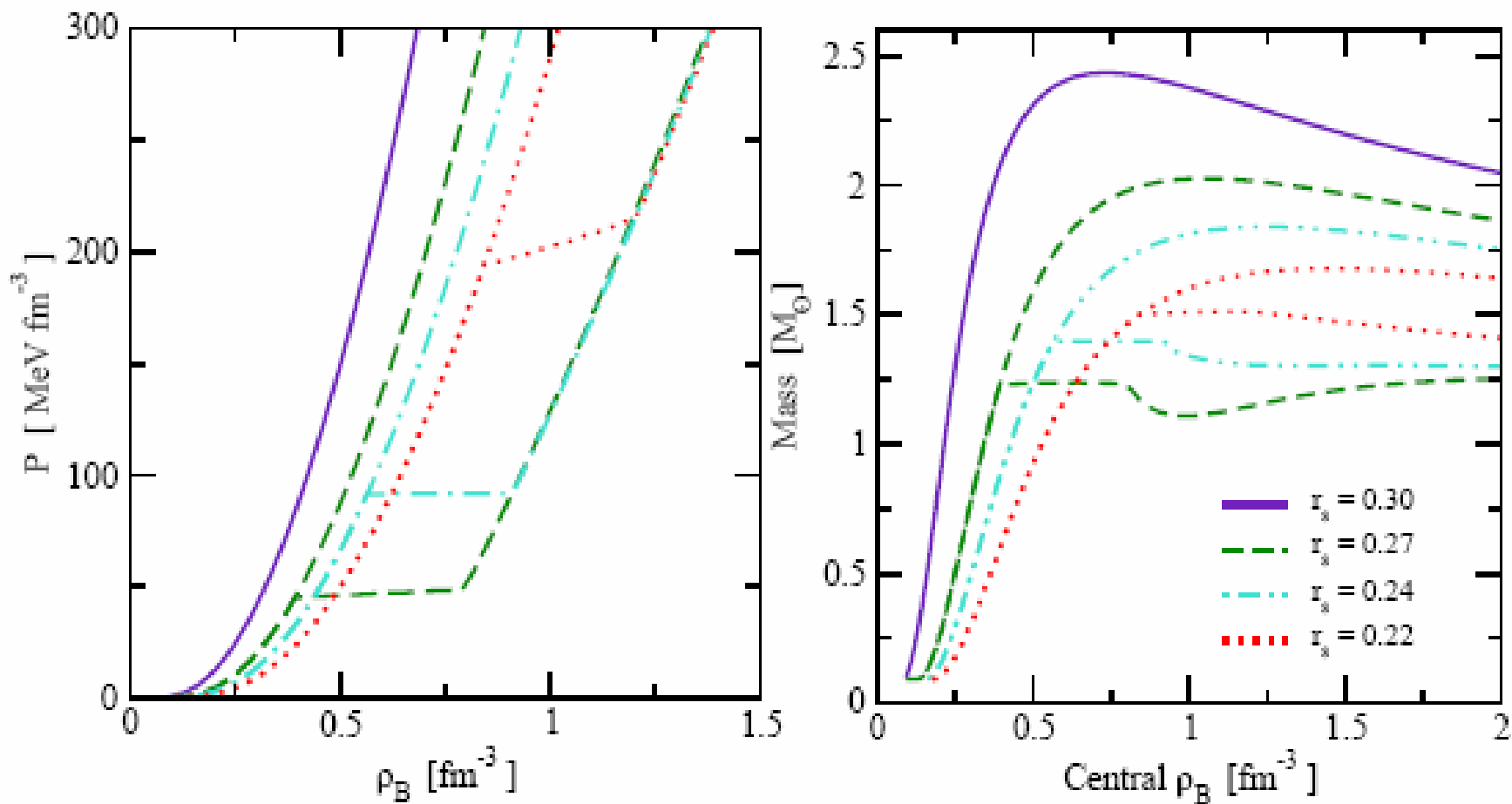


# Phases of Dense Matter : NM ( $\rightarrow$ NQM) $\rightarrow$ SQM



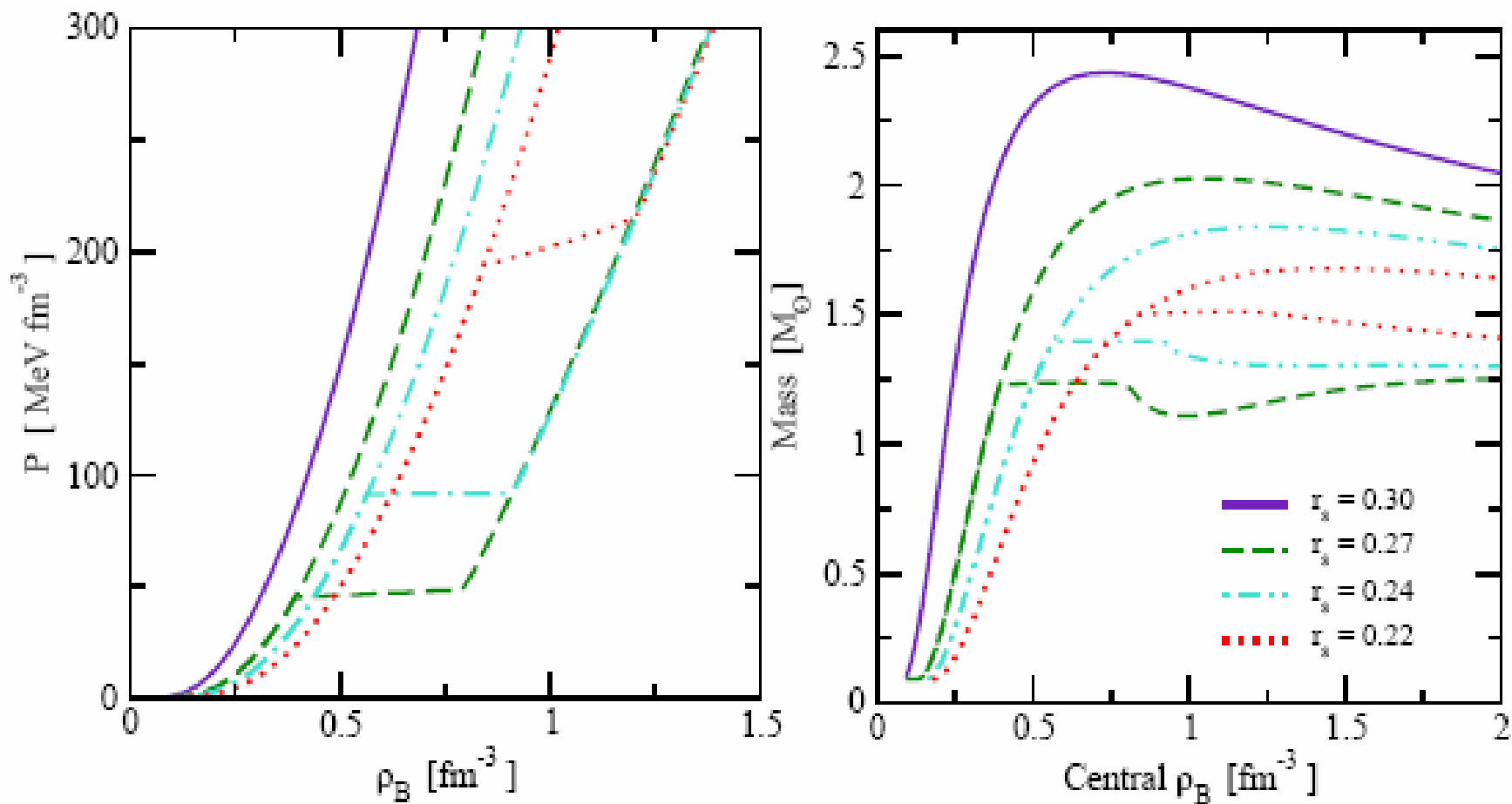
Lawley, Bentz, AWT, nucl-th/0602014 (J Phys G)

# EOS of Dense Matter – n Star Properties



Naturally leads to low mass, hybrid n stars with masses  $\sim$  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....**



# Summary-1

- For dense matter relativity matters
- 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  $\Lambda$  N,  $\Sigma$  N,  $\Xi$  N forces (not yet published)
- Availability of realistic, density dependent Hyperon-N forces is essential for  $\rho > 2-3 \rho_0$
- Covariant version can be tested experimentally – Jlab
- Already remarkable results for NM, NQM, SQM in n stars

# Special Mentions.....





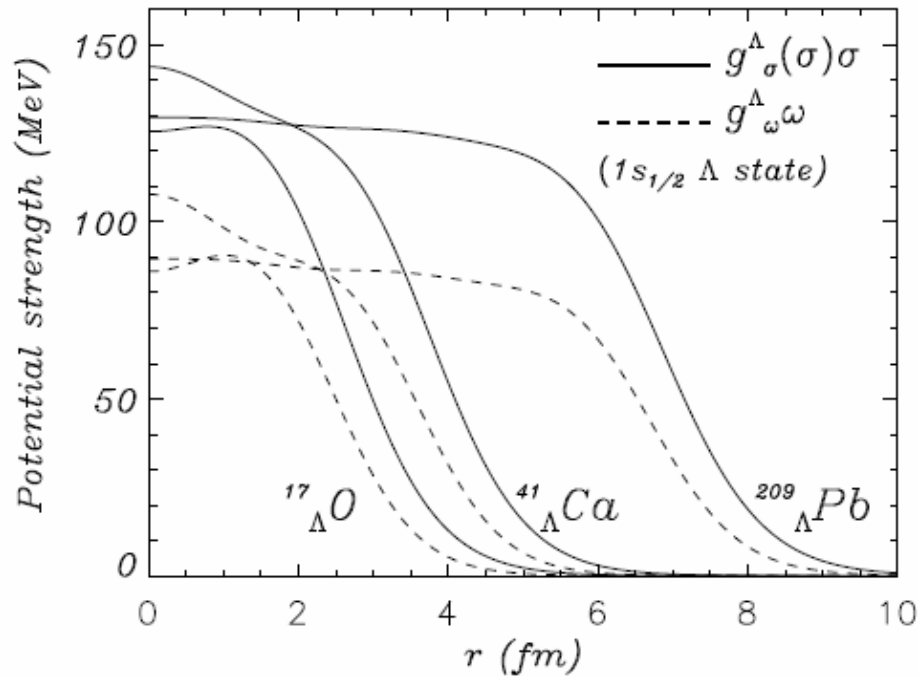
# Finally: Apply to Shell Structure as $N - Z \downarrow$

- 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.)



# Finite Hypernuclei in original QMC Model



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

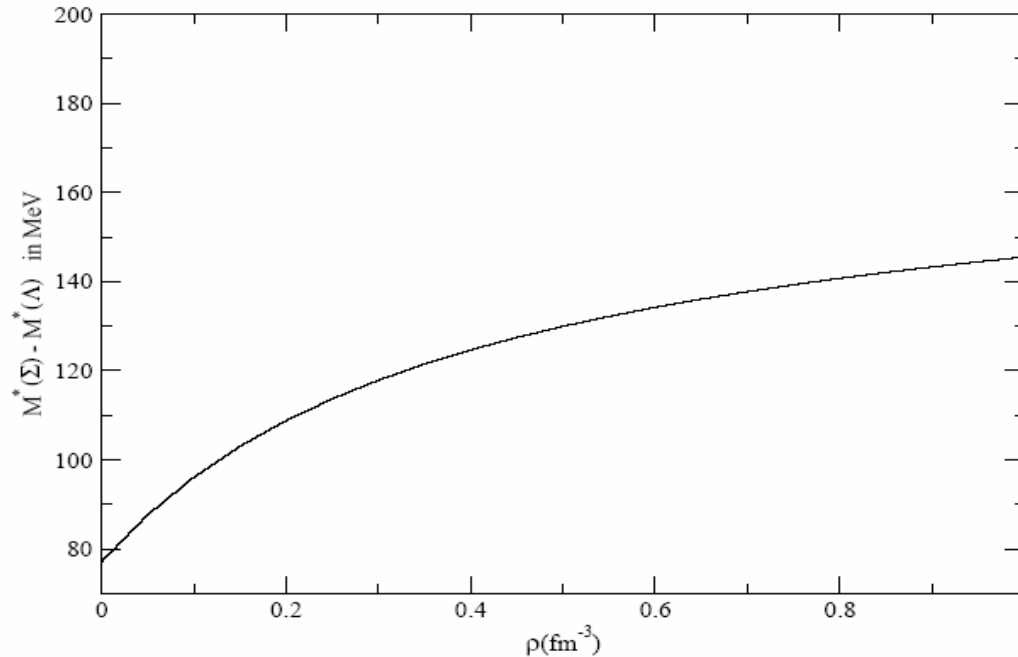
**BUT Σ hypernuclei were also  
bound – estimate of Σ - Λ  
conversion reduces binding in Pb by ~ 7 MeV**

	$^{208}_{\Lambda}\text{Pb}$ (Expt.)	$^{209}_{\Lambda}\text{Pb}$
$1s_{1/2}$	-27.0	-27.0**
$1p_{3/2}$		-23.4
$1p_{1/2}$	-22.0 (1p)	-23.4
$1d_{5/2}$		-19.1
$2s_{1/2}$		-17.6
$1d_{3/2}$	-17.0 (1d)	-19.1
$1f_{7/2}$		-14.4
$2p_{3/2}$		-12.4
$1f_{5/2}$	-12.0 (1f)	-14.3
$2p_{1/2}$		-12.4
$1g_{9/2}$		-9.3
$1g_{7/2}$	-7.0 (1g)	-9.2
$1h_{11/2}$		-3.9
$2d_{5/2}$		-7.0
$2d_{3/2}$		-7.0
$1h_{9/2}$		-3.8

# Latest QMC: Includes Medium Modification of Hyperfine Interaction

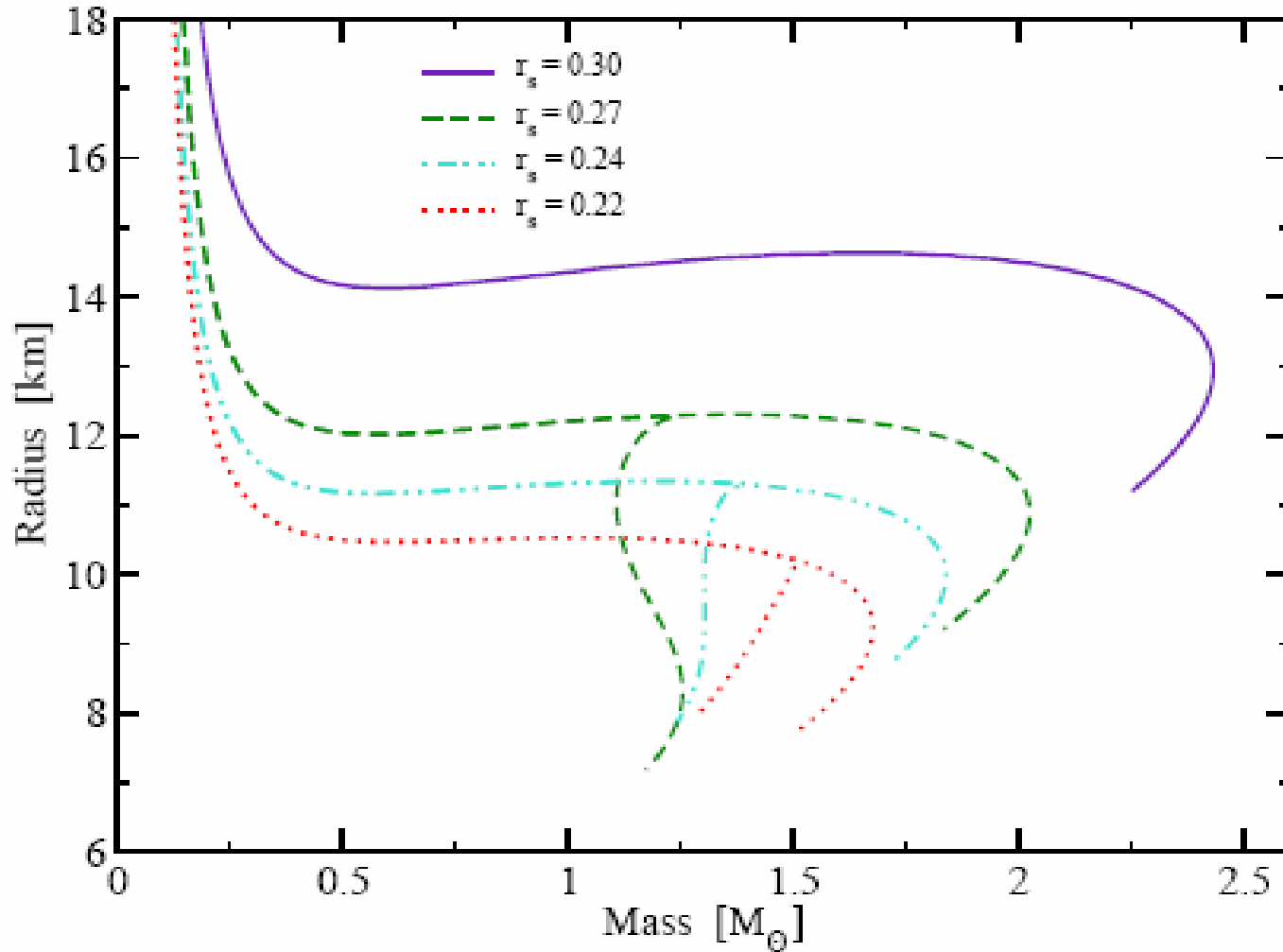
**N -  $\Delta$  and  $\Sigma$  -  $\Lambda$  splitting arise from one-gluon-exchange in MIT Bag Model : as  $\sigma \uparrow$  so does this splitting...**

Difference of Sigma and Lambda effective mass

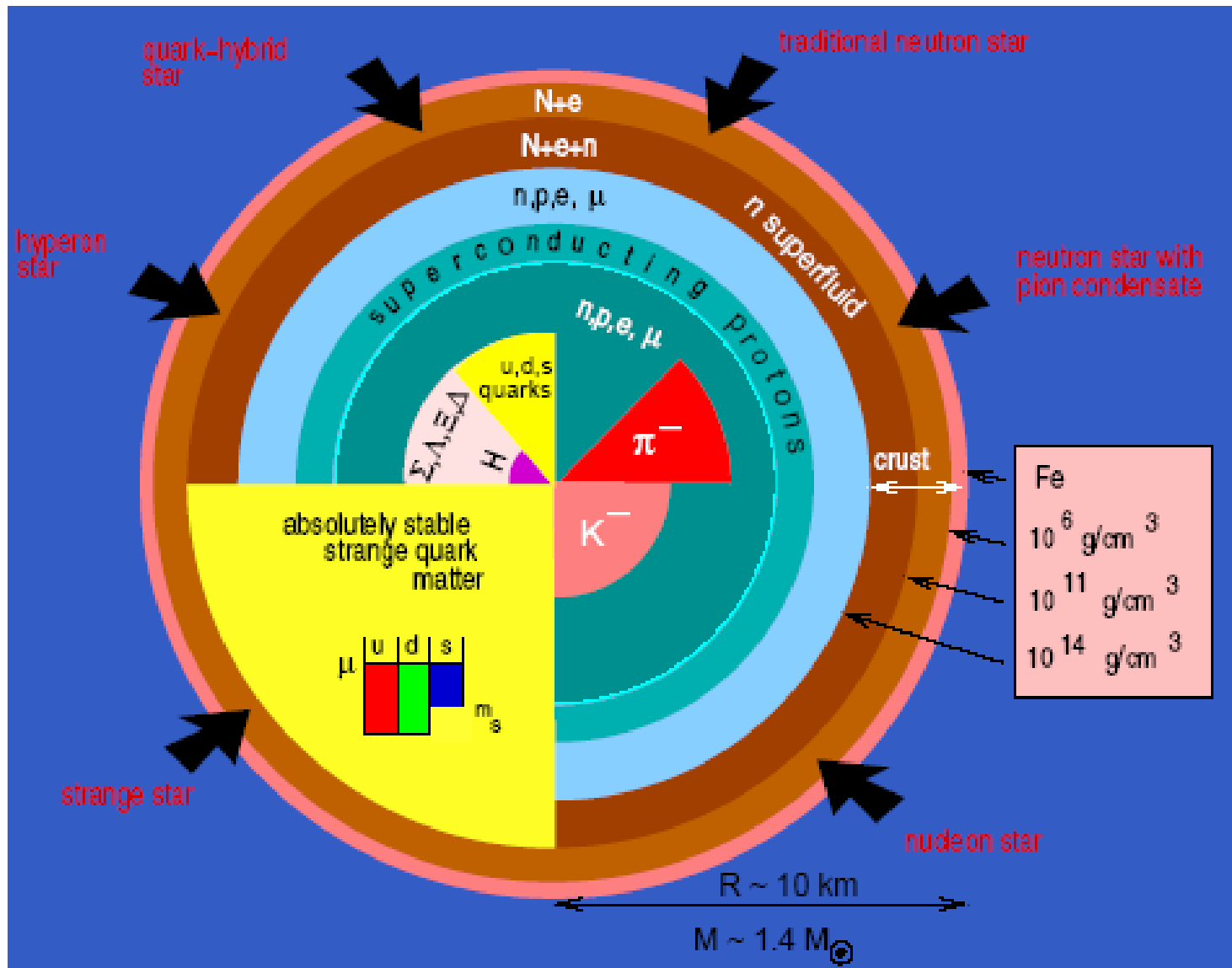


**Guichon, Stone, Thomas, Tsushima: to appear**

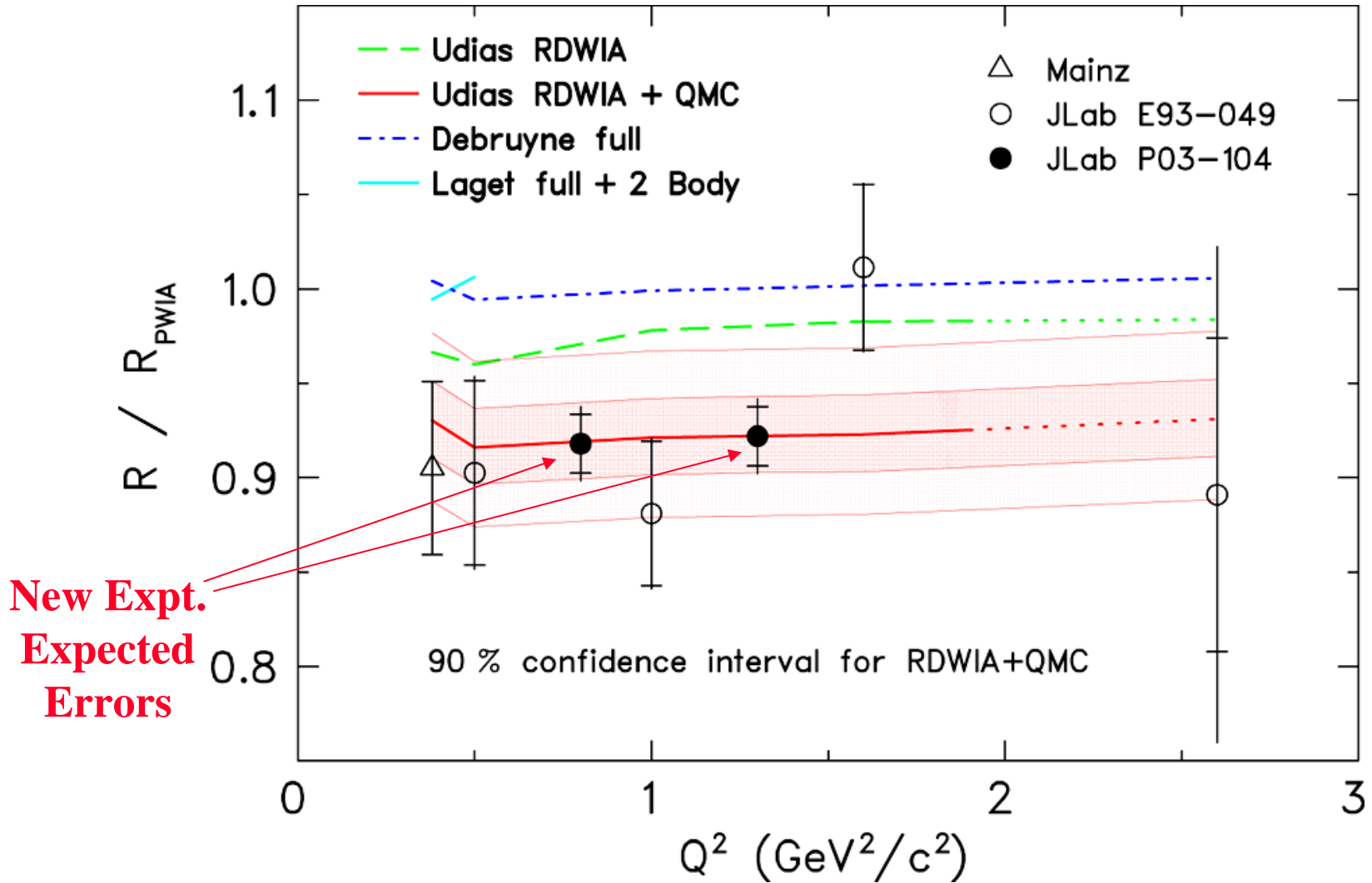
# Mass vs Radius with Consistent Treatment of Hadron Structure and Quark Matter

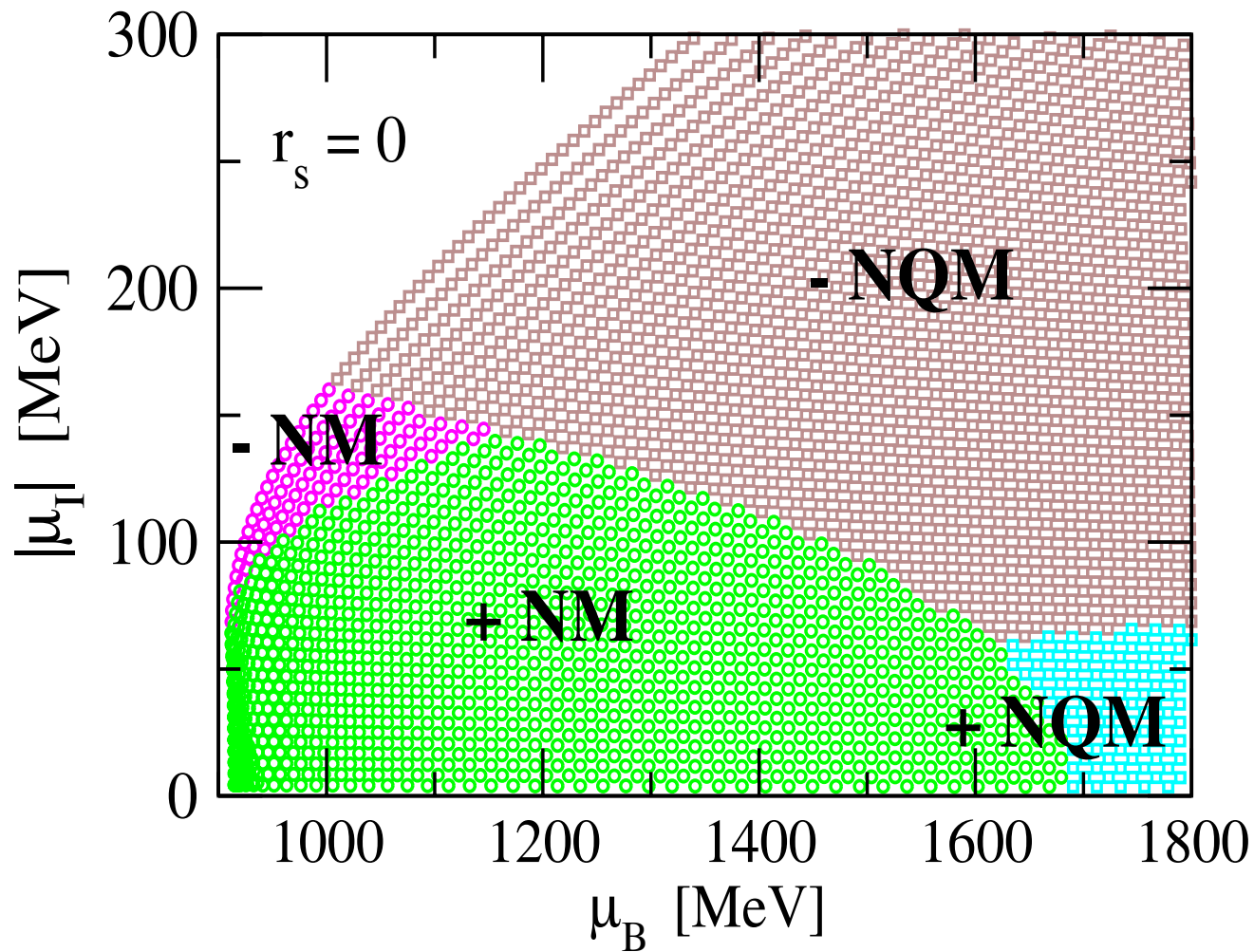




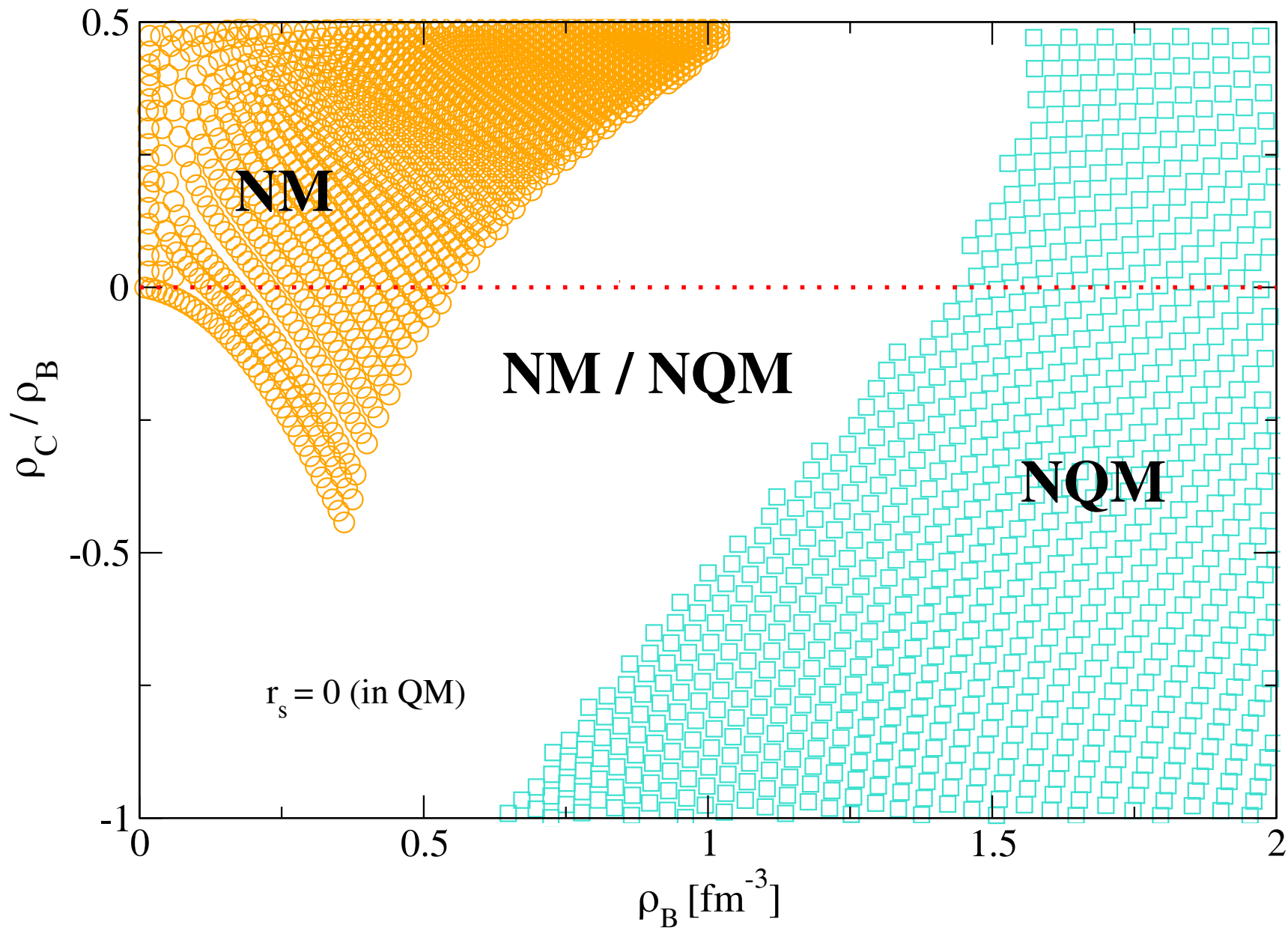


# Jefferson Lab & Mainz





Lawley, Bentz, AWT, nucl-th/0504020 (Phys Lett)



# 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**

**18<sup>th</sup> Nishinomiya Symposium: nucl-th/0411014**  
**Prog. Theor. Phys.**



# Desperate need for data...

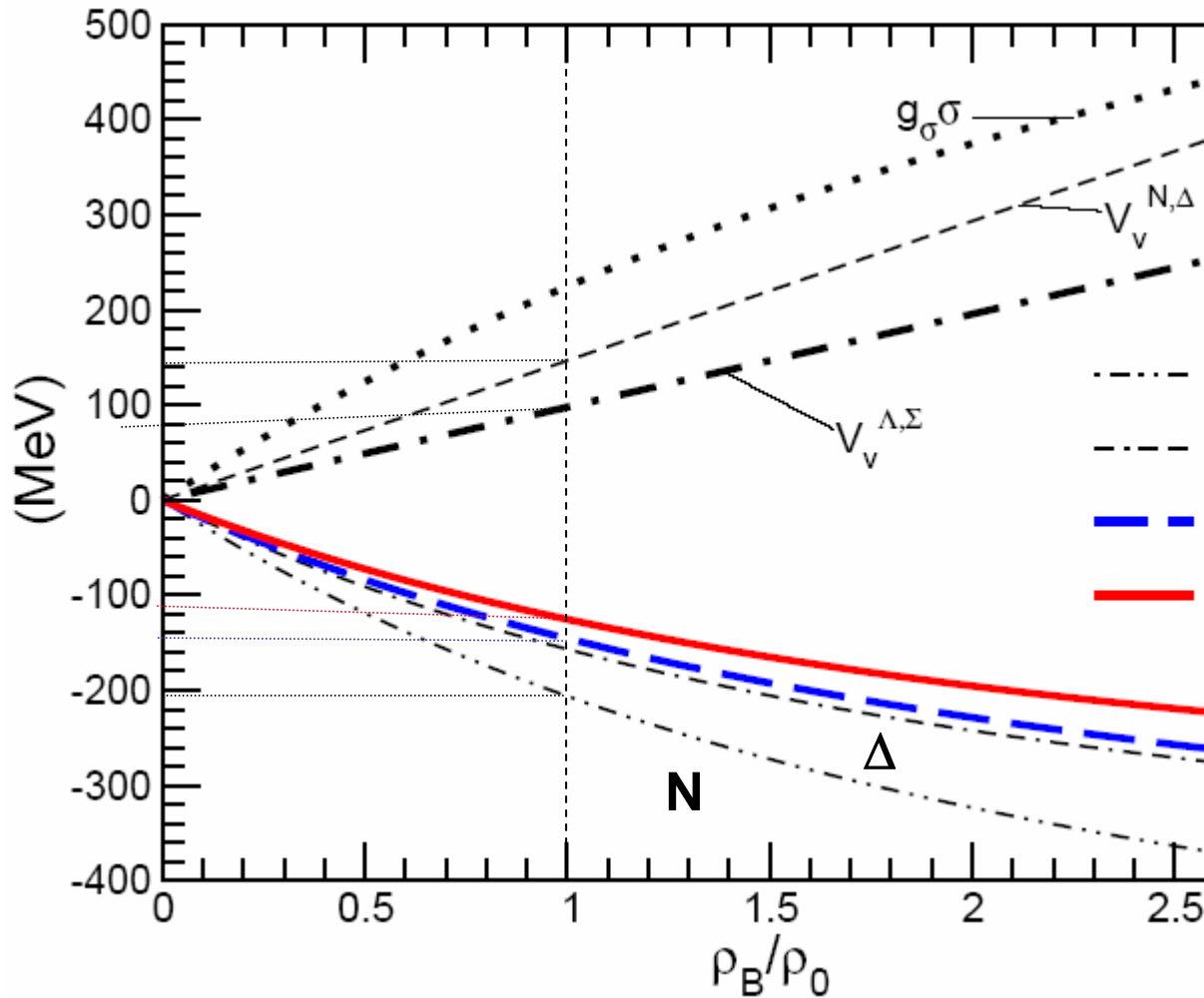
Only one  $\Sigma$  hypernucleus known to be bound

- BUT for doubly strange hypernuclei world has only 6 events (most controversial)
- Would be tremendous help in attempting to understand EOS for dense matter to have real data for  $\Sigma$  and  $\Xi$  hypernuclei!
- If JLab can contribute it would be a major step forward



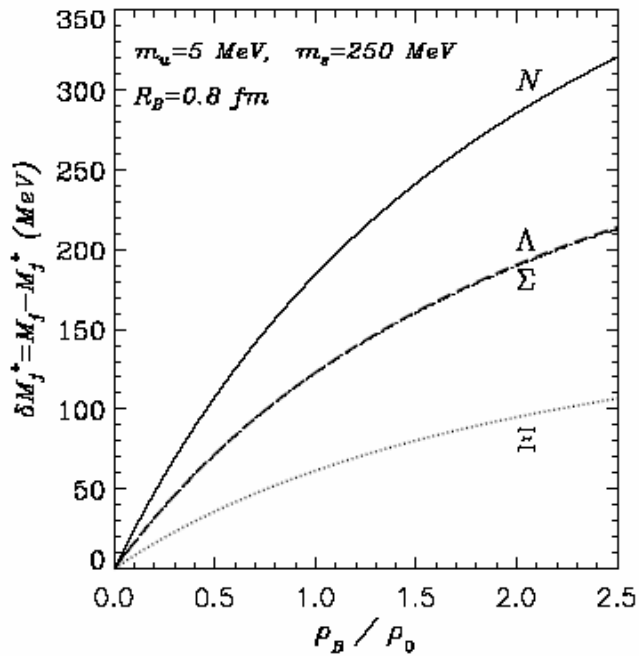
HKS Hall C - JLab

# Nuclear Matter: New QMC including Hyperfine Int<sup>n</sup>



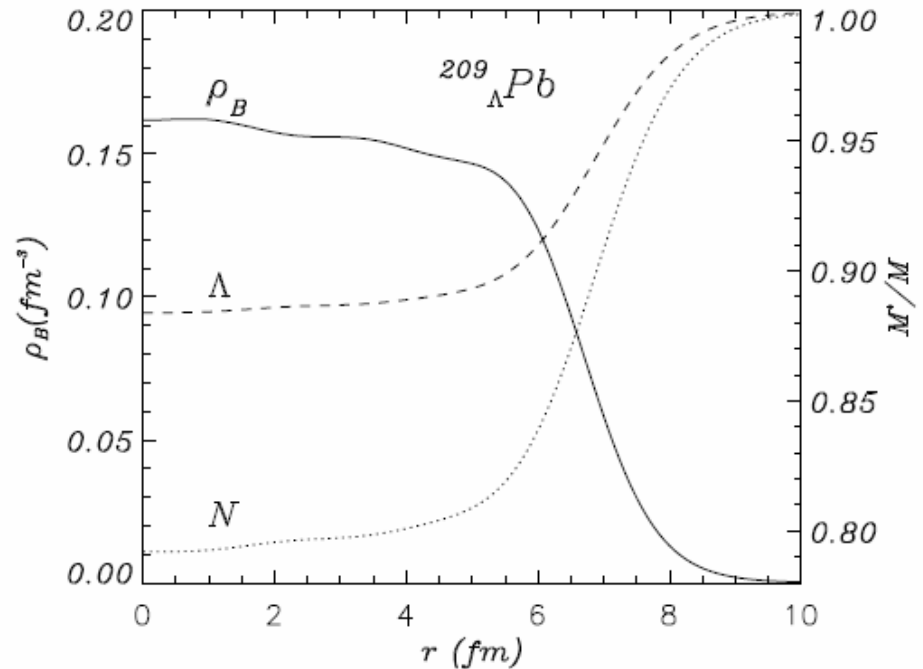
Resolves issue of  $\Sigma$  binding!

# Back to Hyperons in Matter: Original QMC Model



In Pb  $\sim 2:1$

Nuclear Matter:  $\delta M_H$   
 N:  $\Lambda$ :  $\Xi \sim 3:2:1$



Tsushima et al., N P A630 (1998) 691



