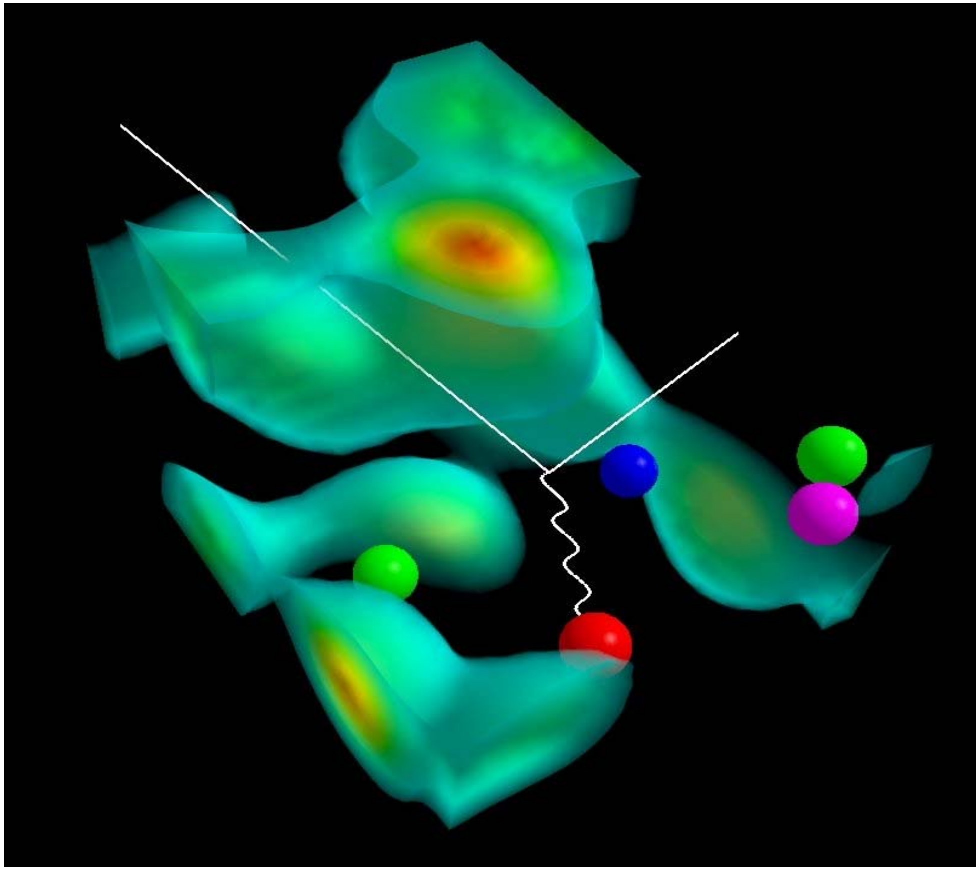
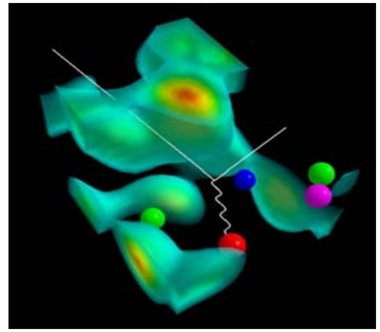
Origin of the Nuclear EOS in Hadronic Physics and QCD



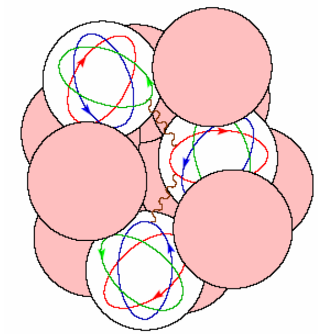
Anthony W. Thomas

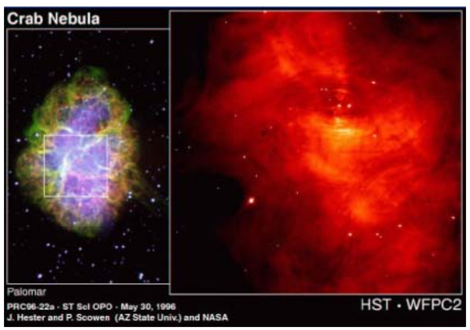
XXX Symposium on Nuclear Physics - Cocoyoc: Jan 5th 2007

Λ, Ξ, ω, D, J/Ψ …… in nuclear matter



QCD & hadron structure

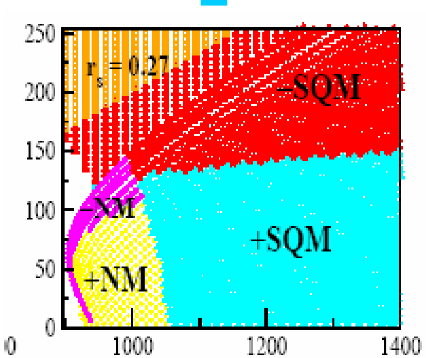




n star

∞ 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 (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

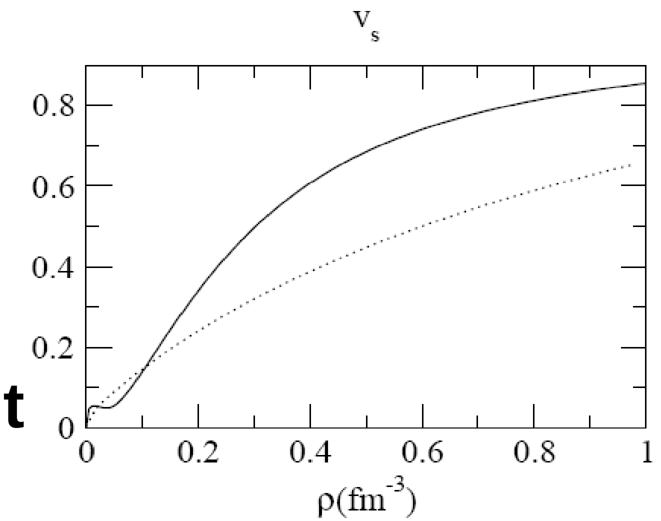
- Classical implementation is Walecka model

  ⇒ $m_N^* / m_N \sim 0.5$ at 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)?**

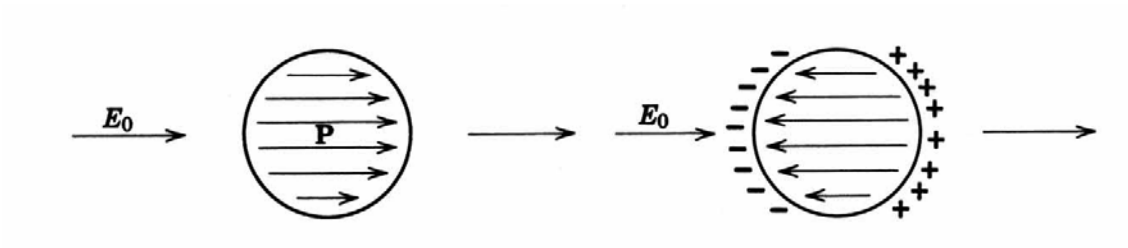
  - π : but easily added and irrelevant in MFA

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

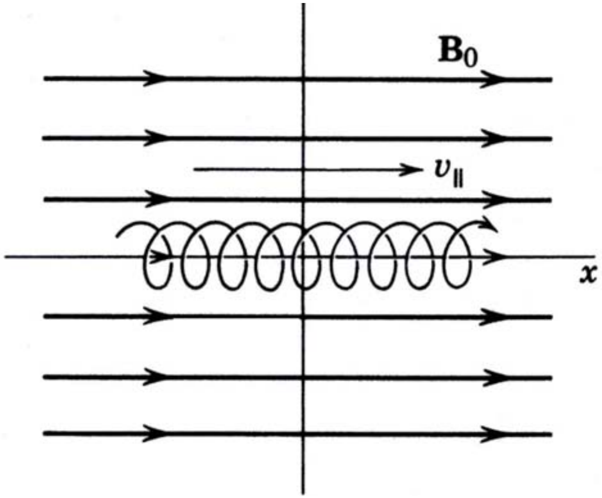
What happens if we put an atom in a strong electric field?

Jackson ⇒

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!)



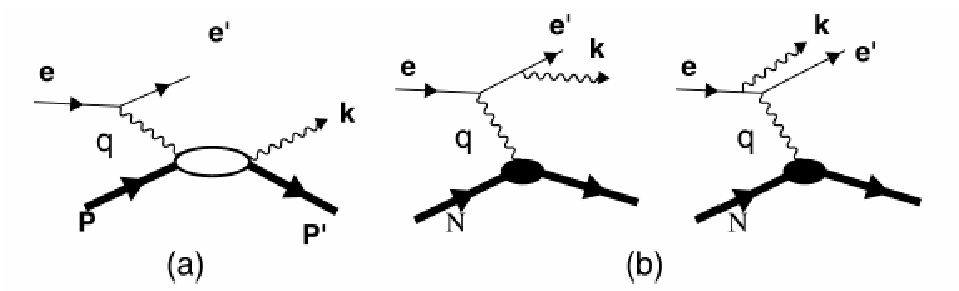
Electric & Magnetic Polarizabilities of Nucleon are Measured

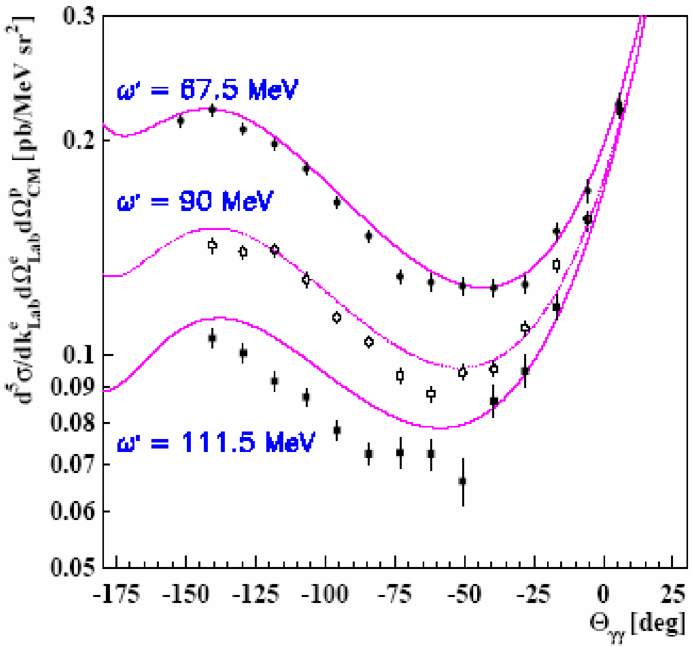
e.g. Compton scattering:

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

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

Also Virtual Compton Scattering ⇒ GPs



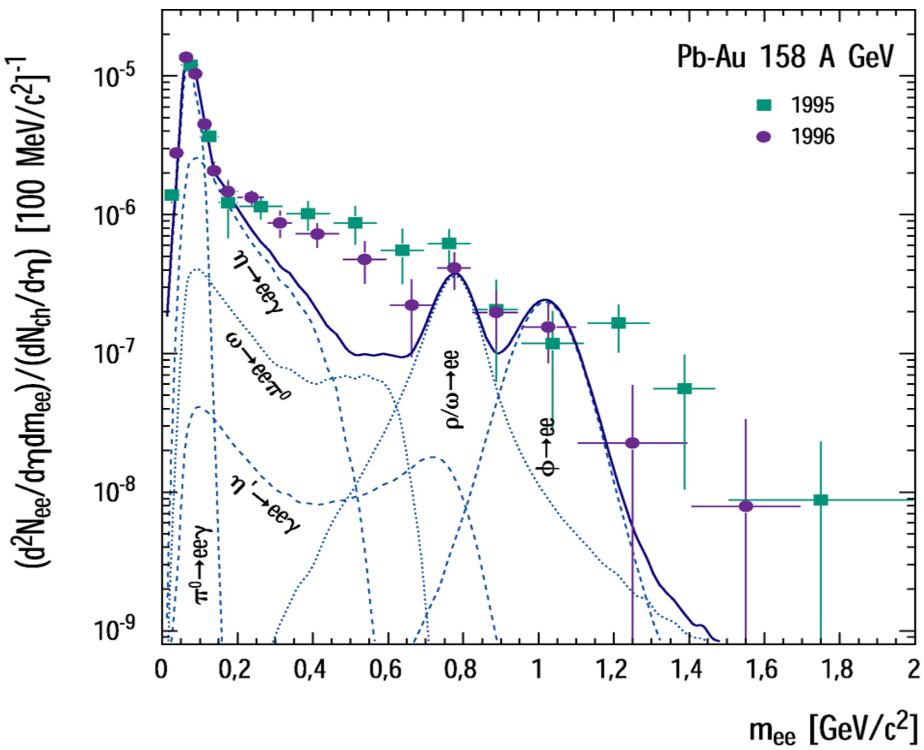


So what?

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 ⇒ 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 ≡ 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)

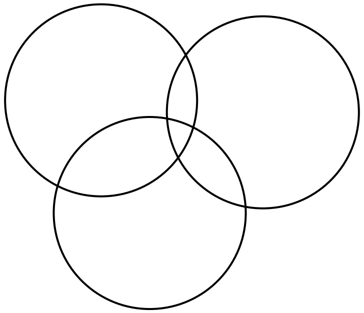
source is suppressed as mean scalar field increases (i.e. as density increases)

Summary : Scalar Polarizability

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

- 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!

Great Start: What's Next

Remove small σ field approximation

- Derive density-dependent forms
- Add the pion
- Derive Λ N, Σ N, $\Lambda\,\Lambda$ … 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 < 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

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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^{208}Pb	7.867	7.515	5.5	5.42

$\sim$ 4%

$\sim$ 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

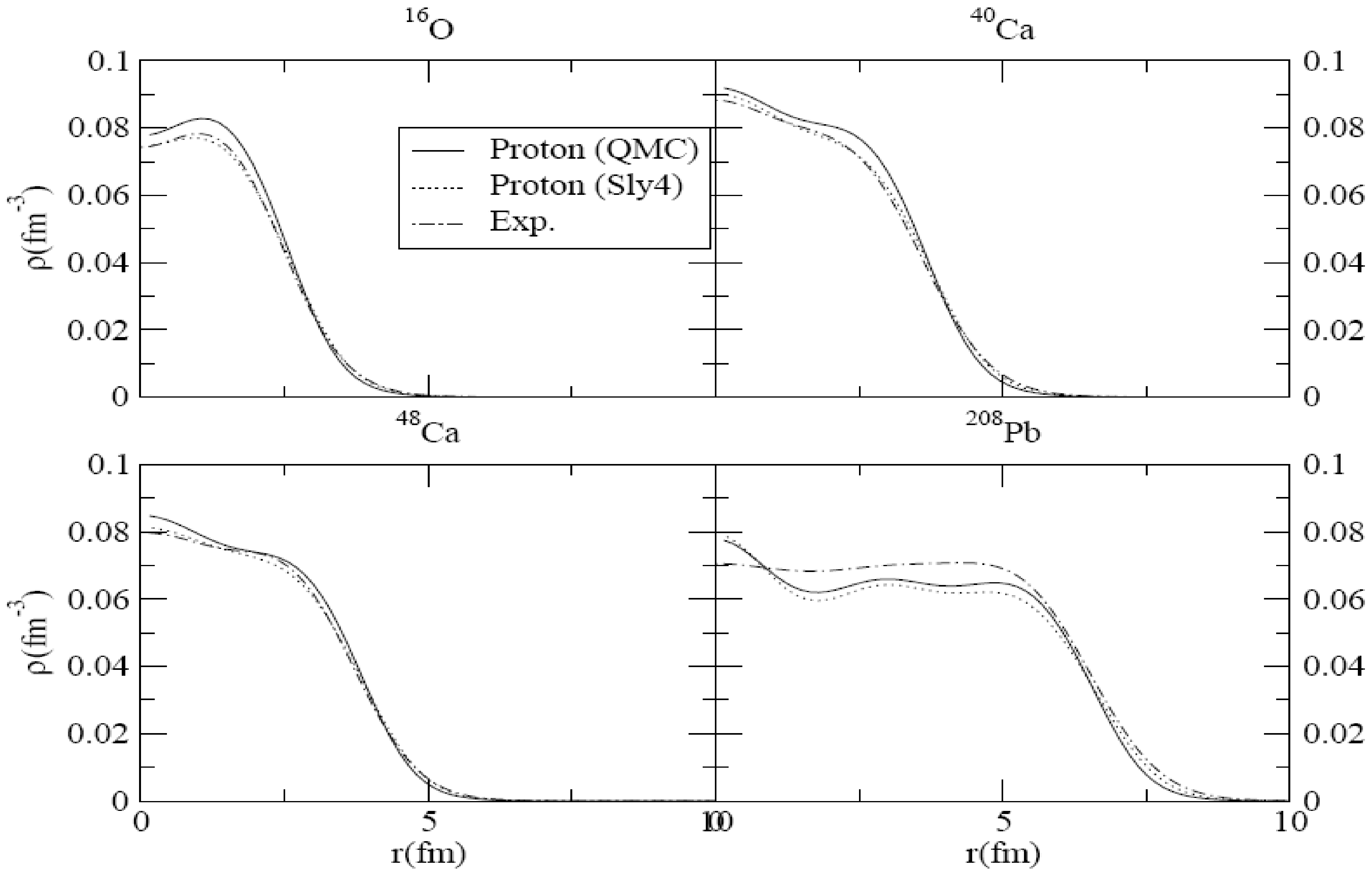
- In comparison with the SkM force:

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

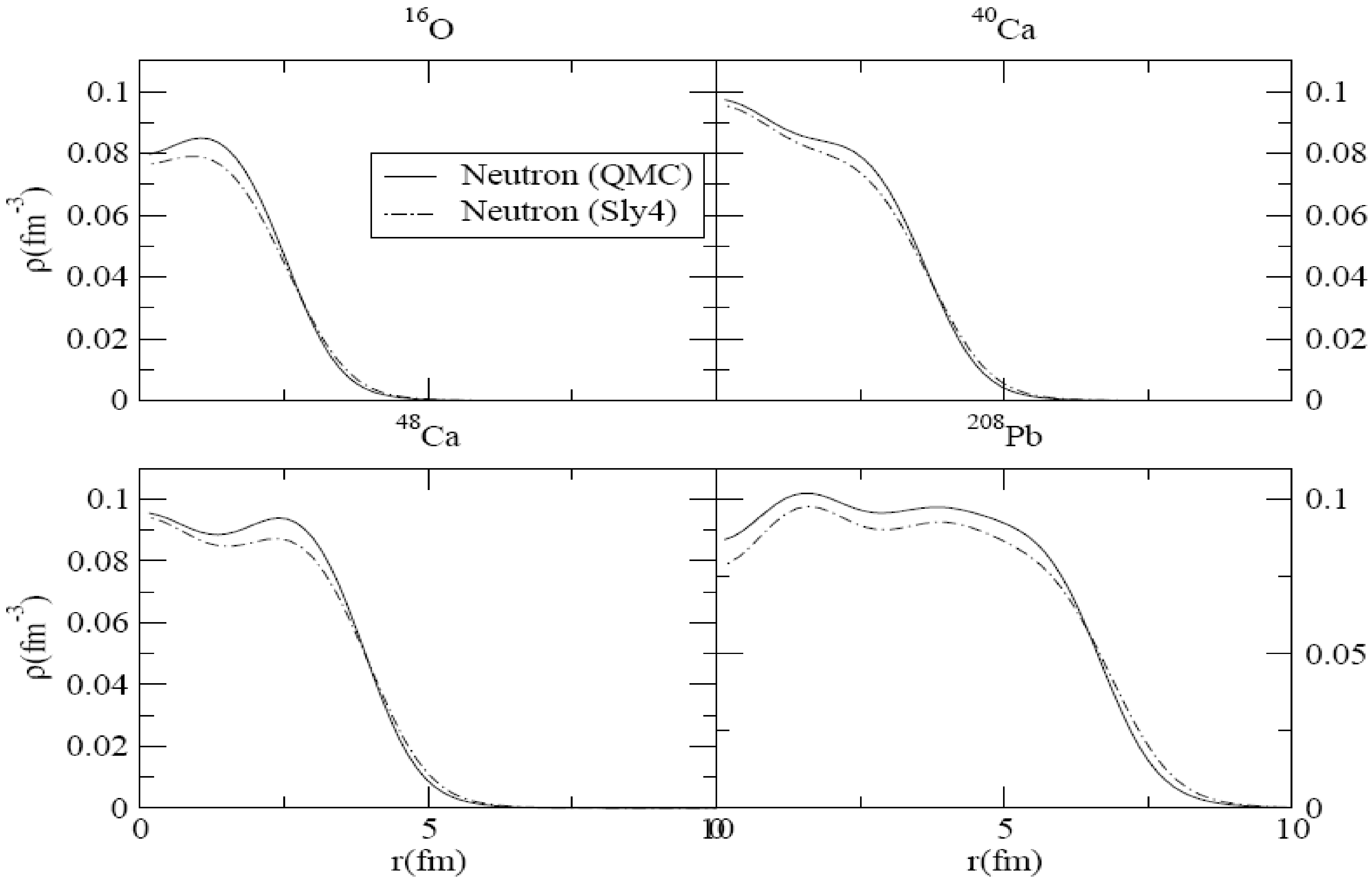
and full energy functional in both cases is:

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

Excellent Agreement with Sly4 for Charge Distributions



Neutron Densities vs Sly4 – also excellent



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

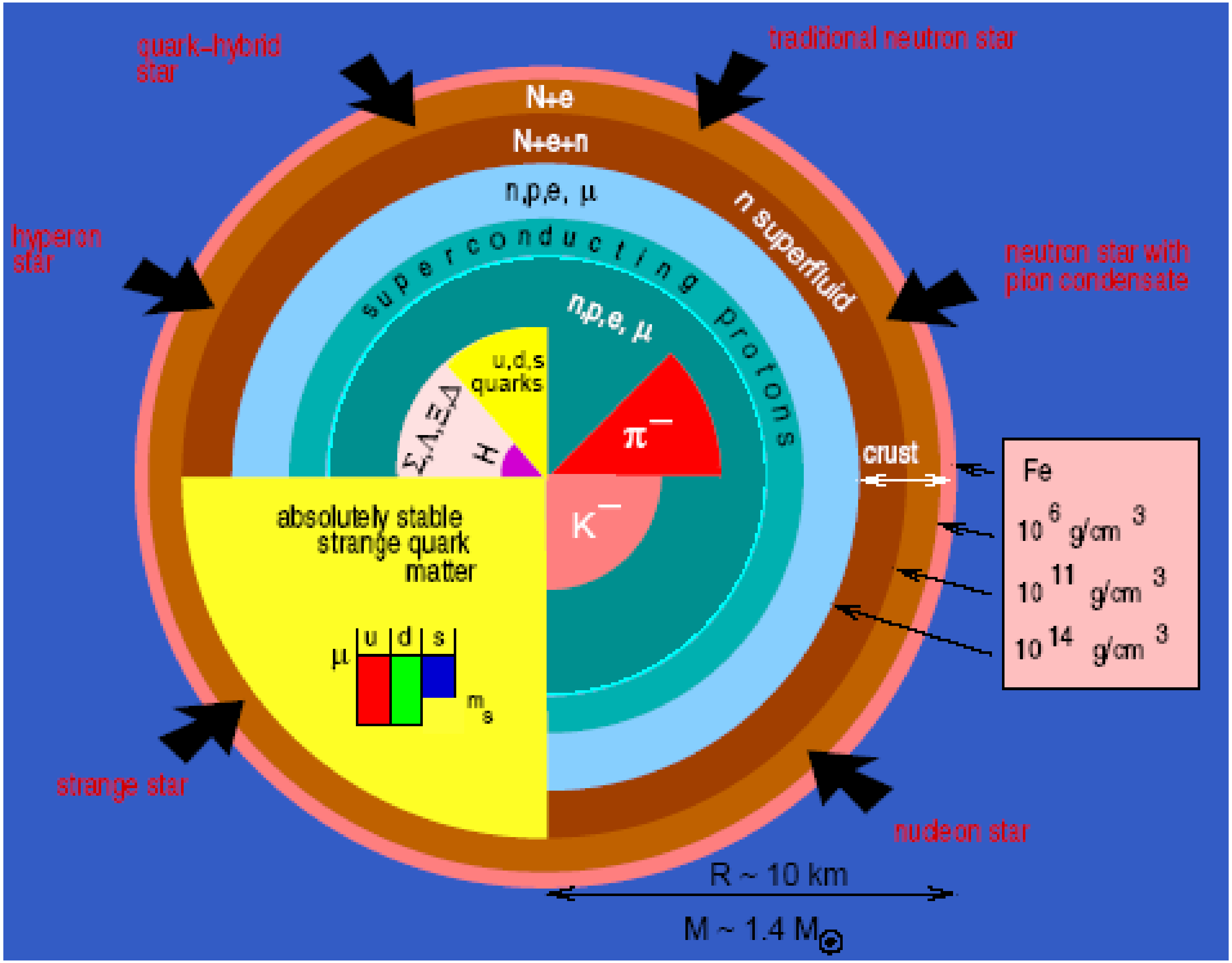
- Calculated variation of two-neutron removal energy at N = 28 as Z varies from Z = 32 (proton drip-line region) to Z = 18 (neutron drip-line region)

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

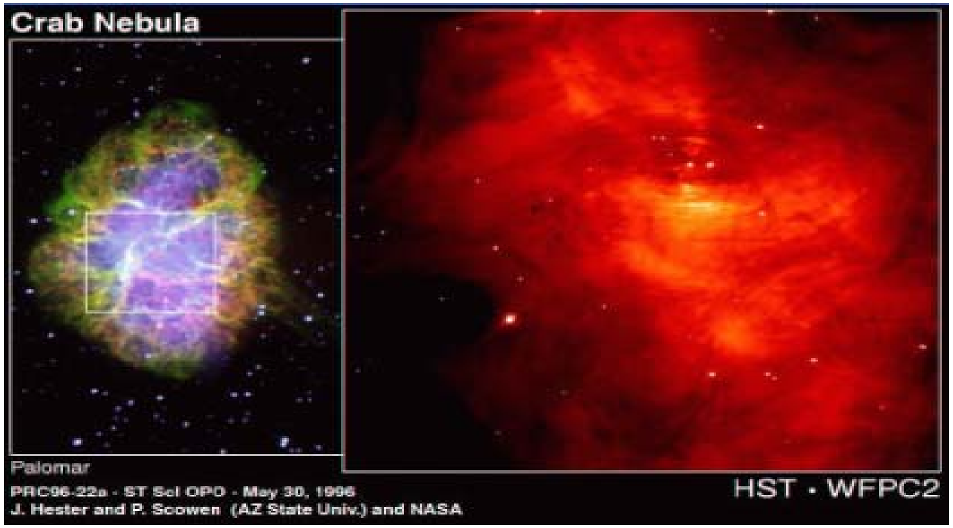
- This strong shell quenching is very similar to Skyrme – HFB calculations of Chabanat et al., Nucl. Phys. A635 (1998) 231

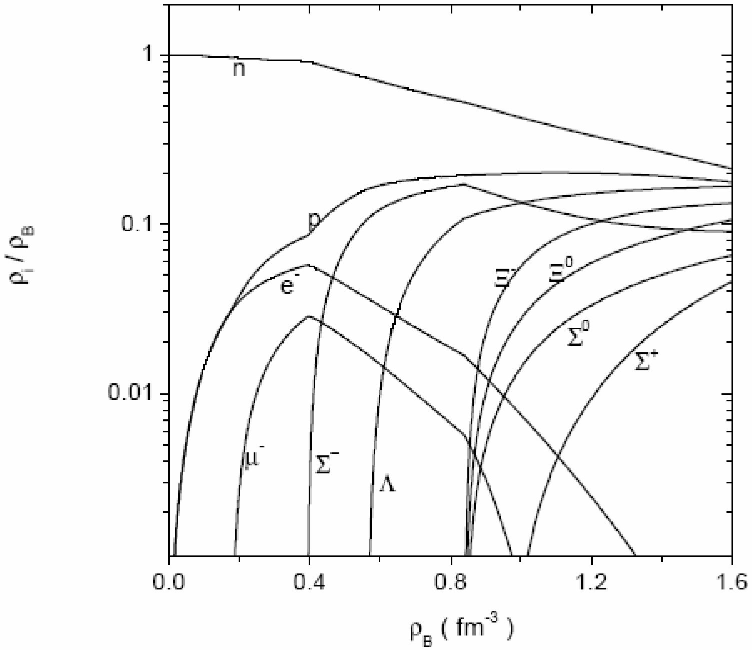
- 2n drip lines appear at about N = 60 for Ni and N = 82 for Zr (/// to predictions for Sly4 – c.f. Chabanat et al.)

Neutron Star Structure is a Fascinating Puzzle



- **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)**





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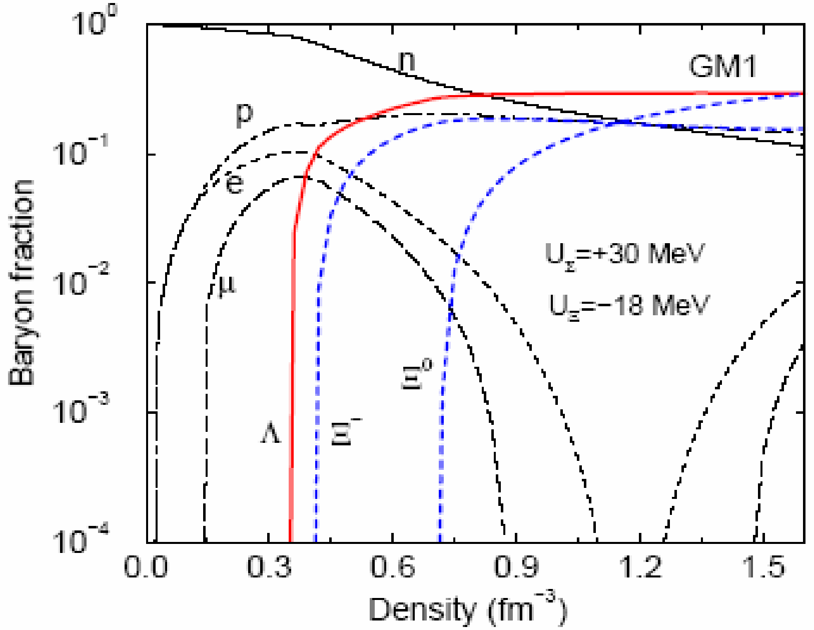
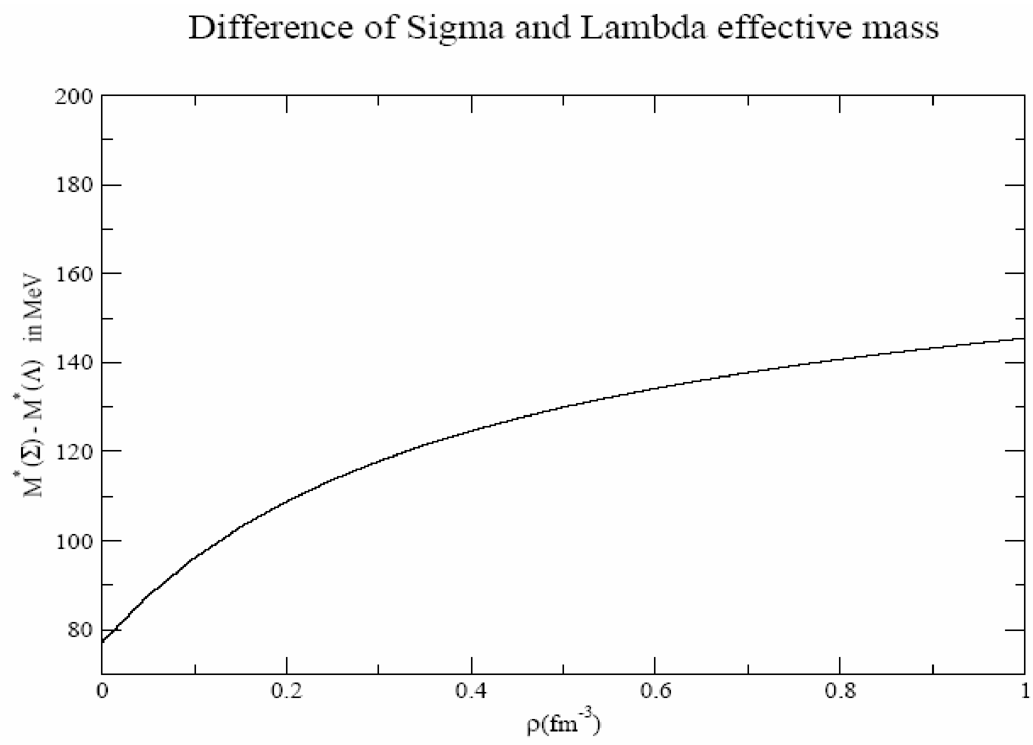


From Schaffner-Bielich (2005)

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…

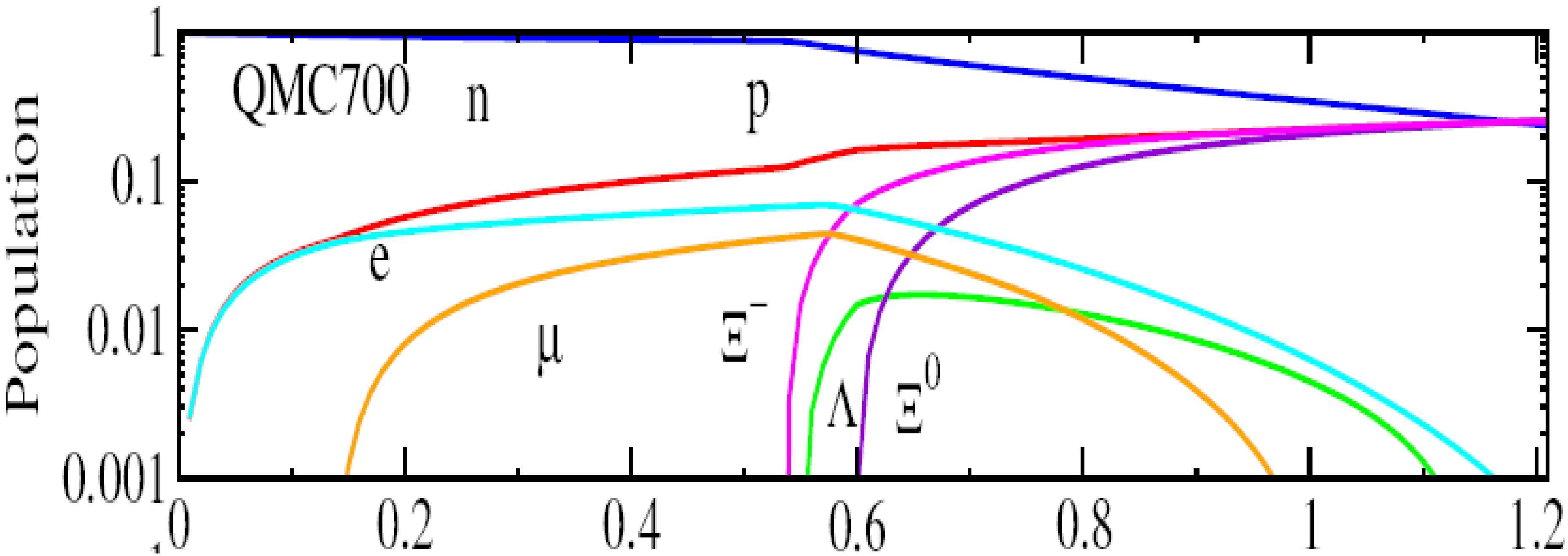


Consequence: Σ hypernuclei unbound/weakly bound

Guichon, Stone, Thomas, Tsushima: to appear

Consequences for Neutron Star

New QMC model, fully relativistic, Hartree-Fock treatment



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

Consequences for Neutron Star

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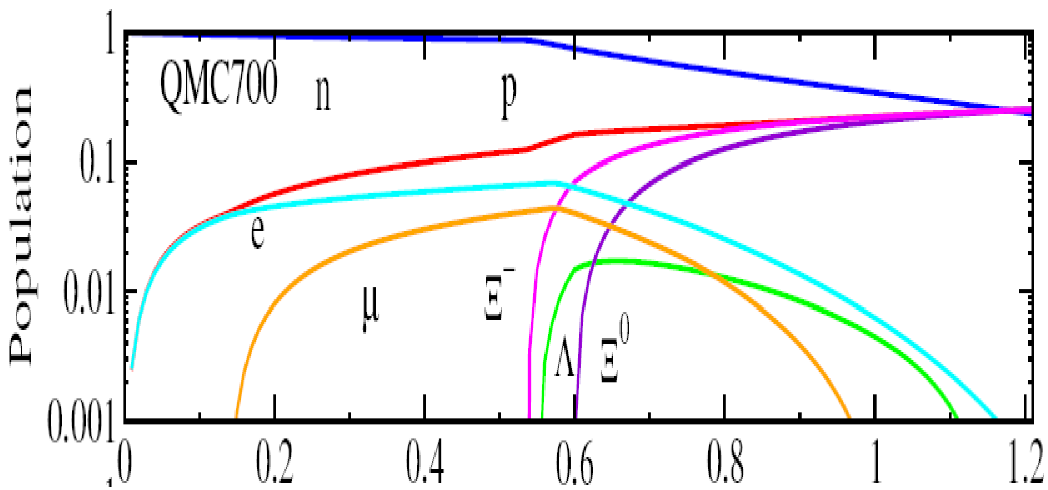
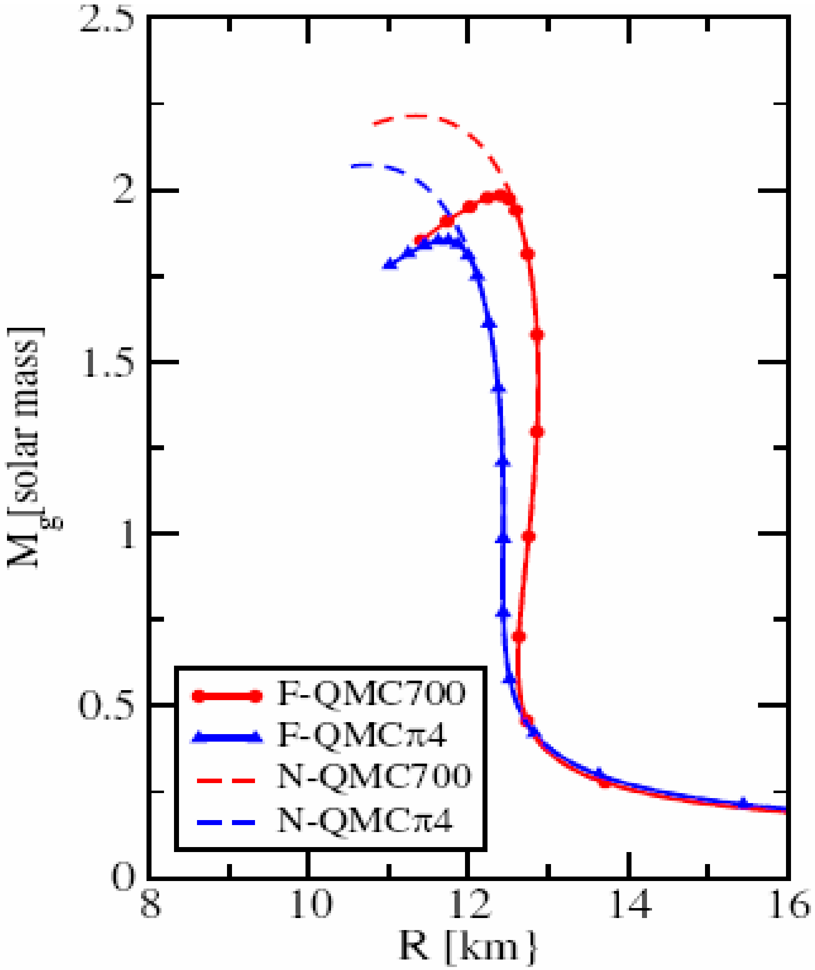




Stone, Guichon, Matevosyan, Thomas, nucl-th/0611030

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

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

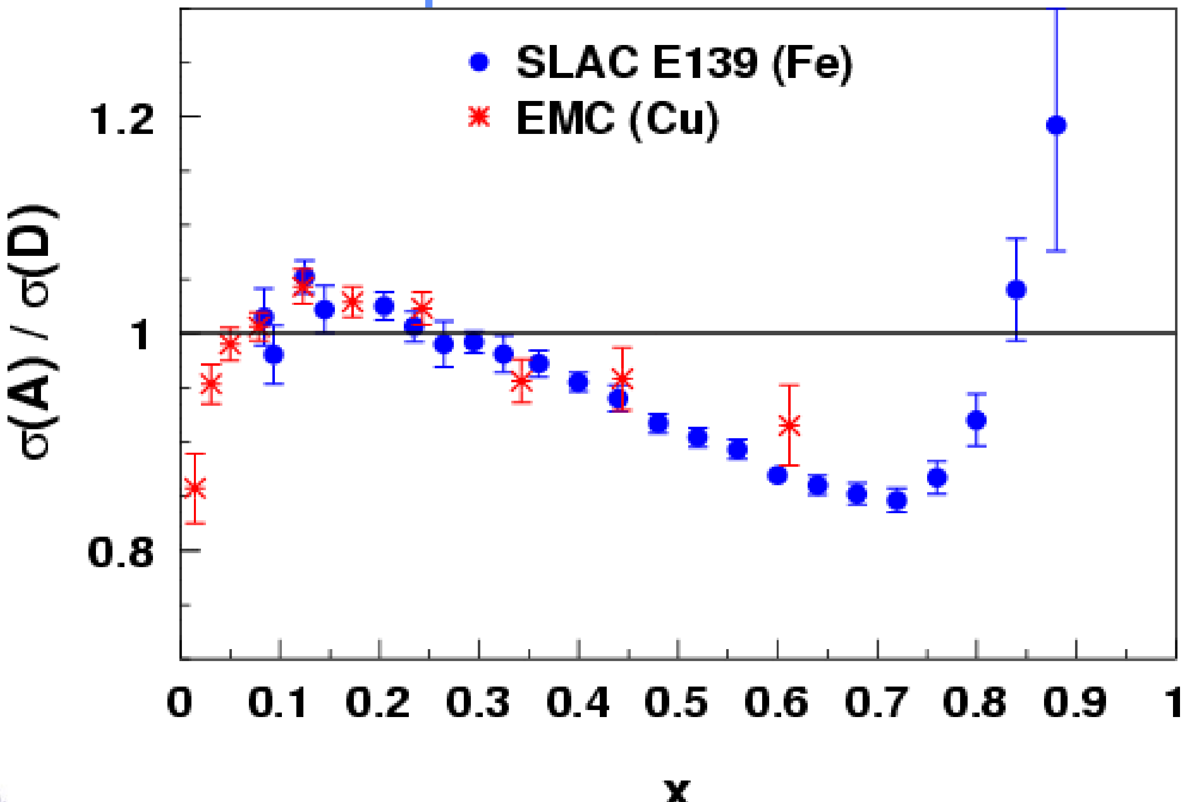
- Applications to neutron stars – including SQM:

- 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?

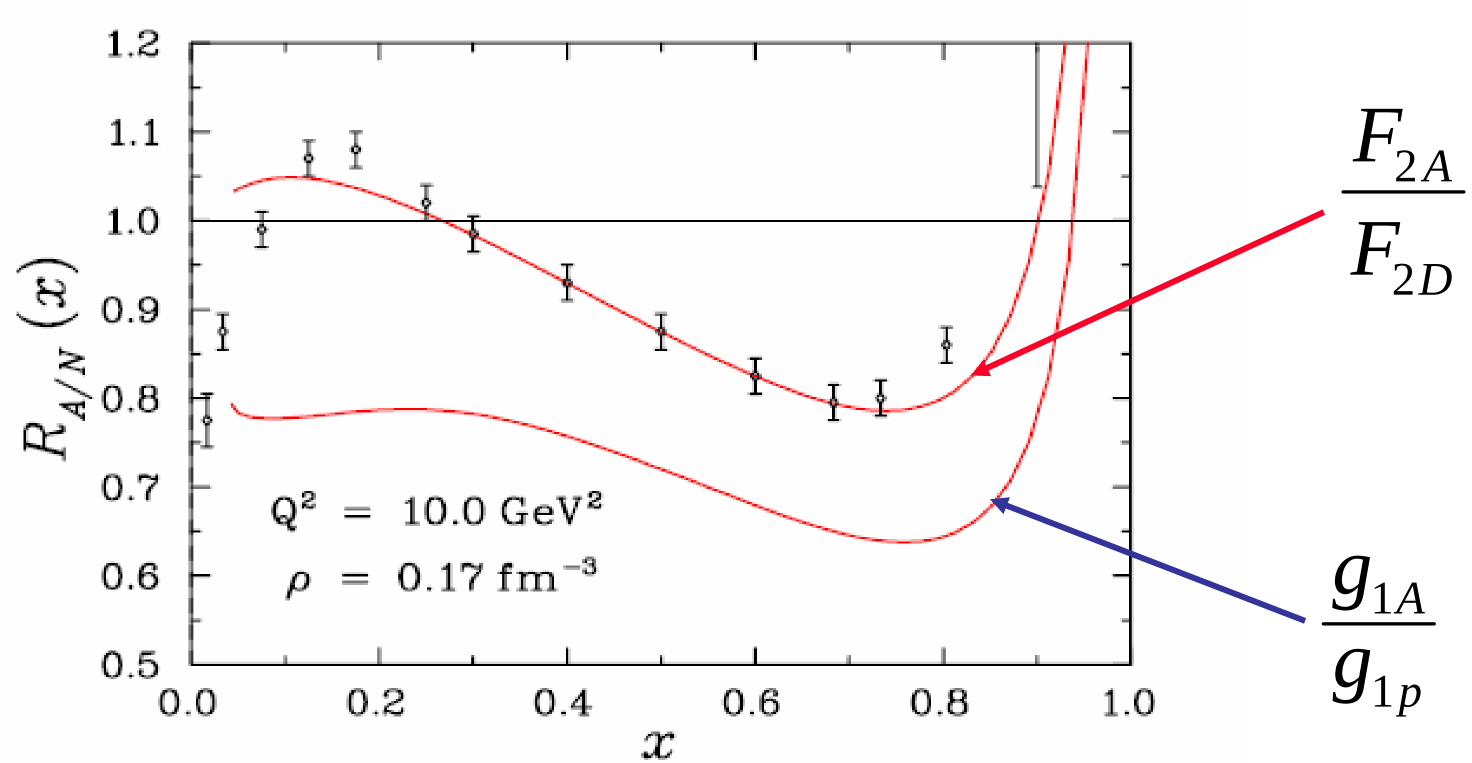


J. Ashman *et al*., Z. Phys. C57, 211 (1993)

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

$g_1(A)$ – "Polarized EMC Effect"

- Calculations described here ⇒ 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

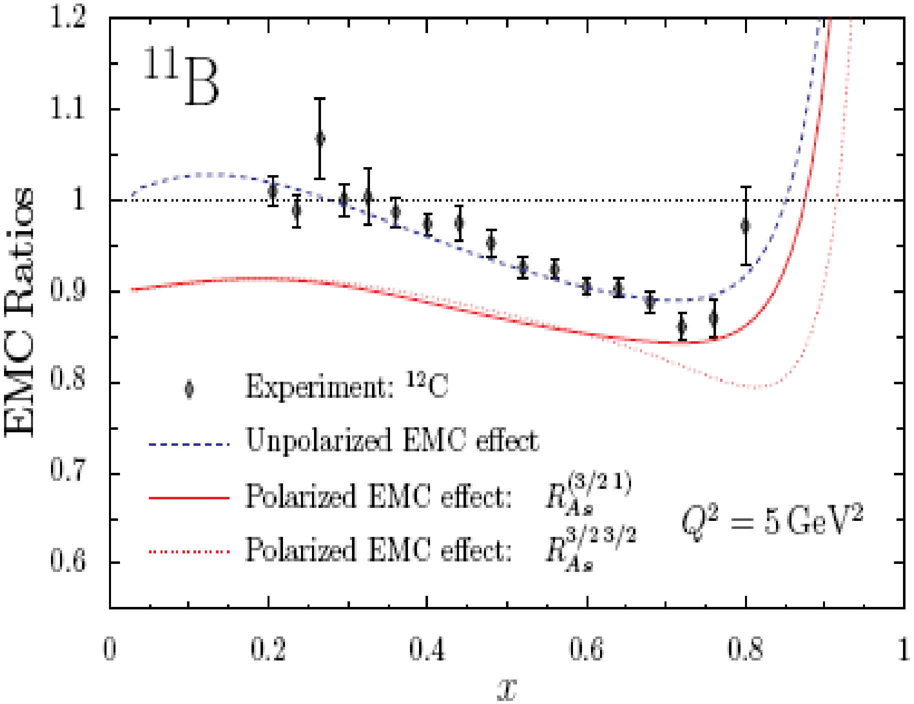


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

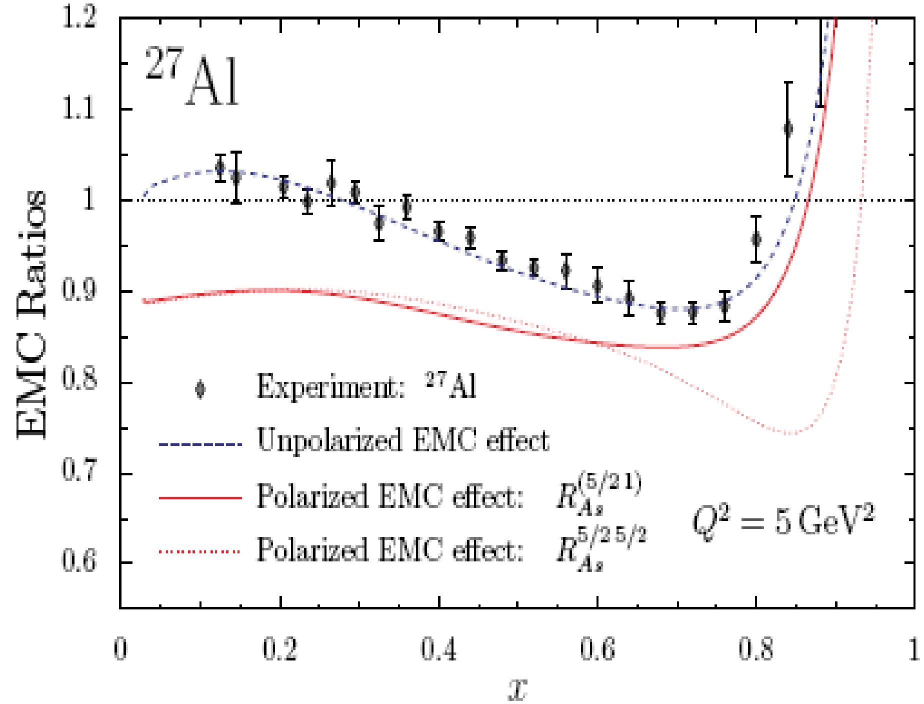
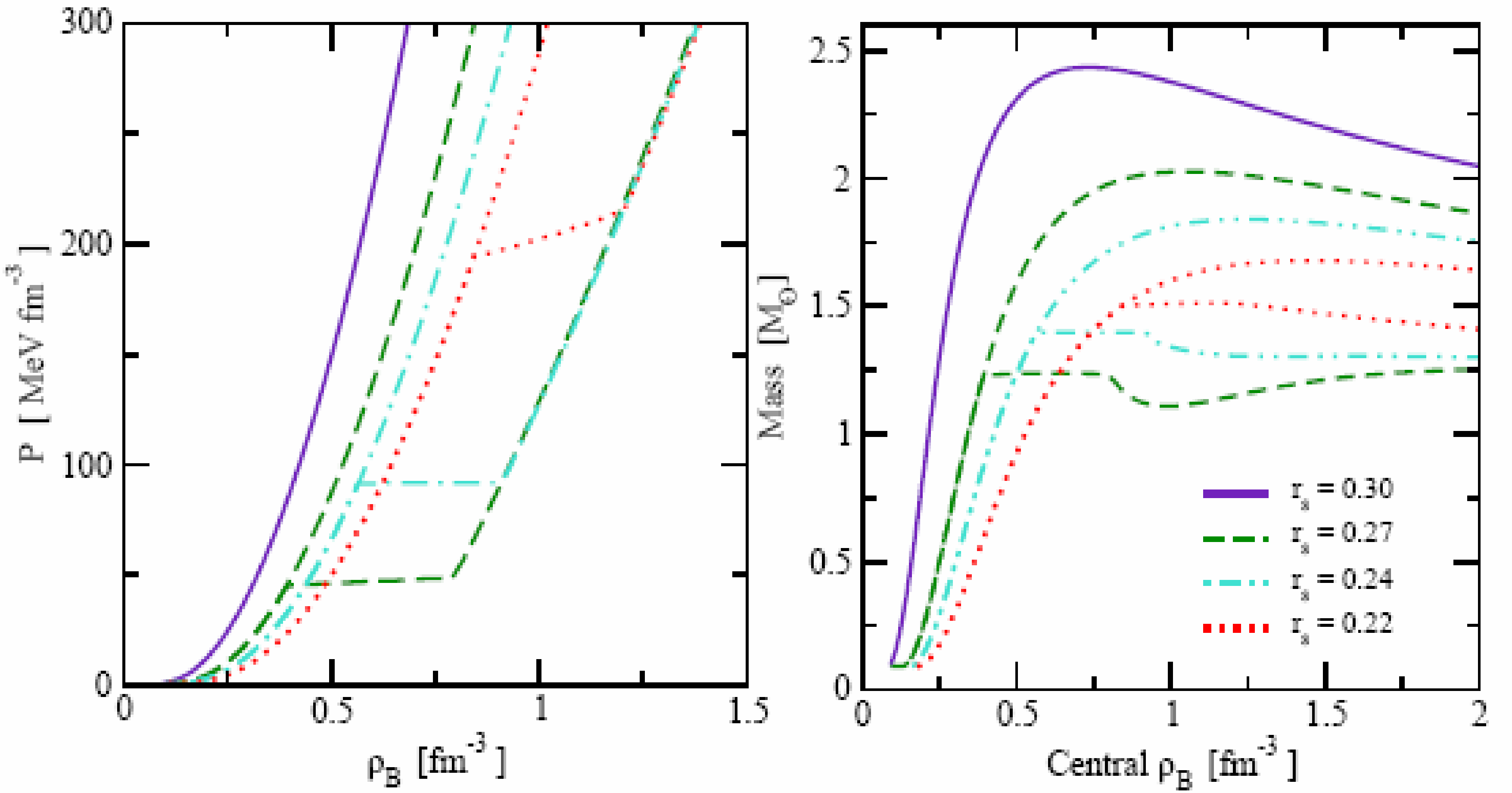


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

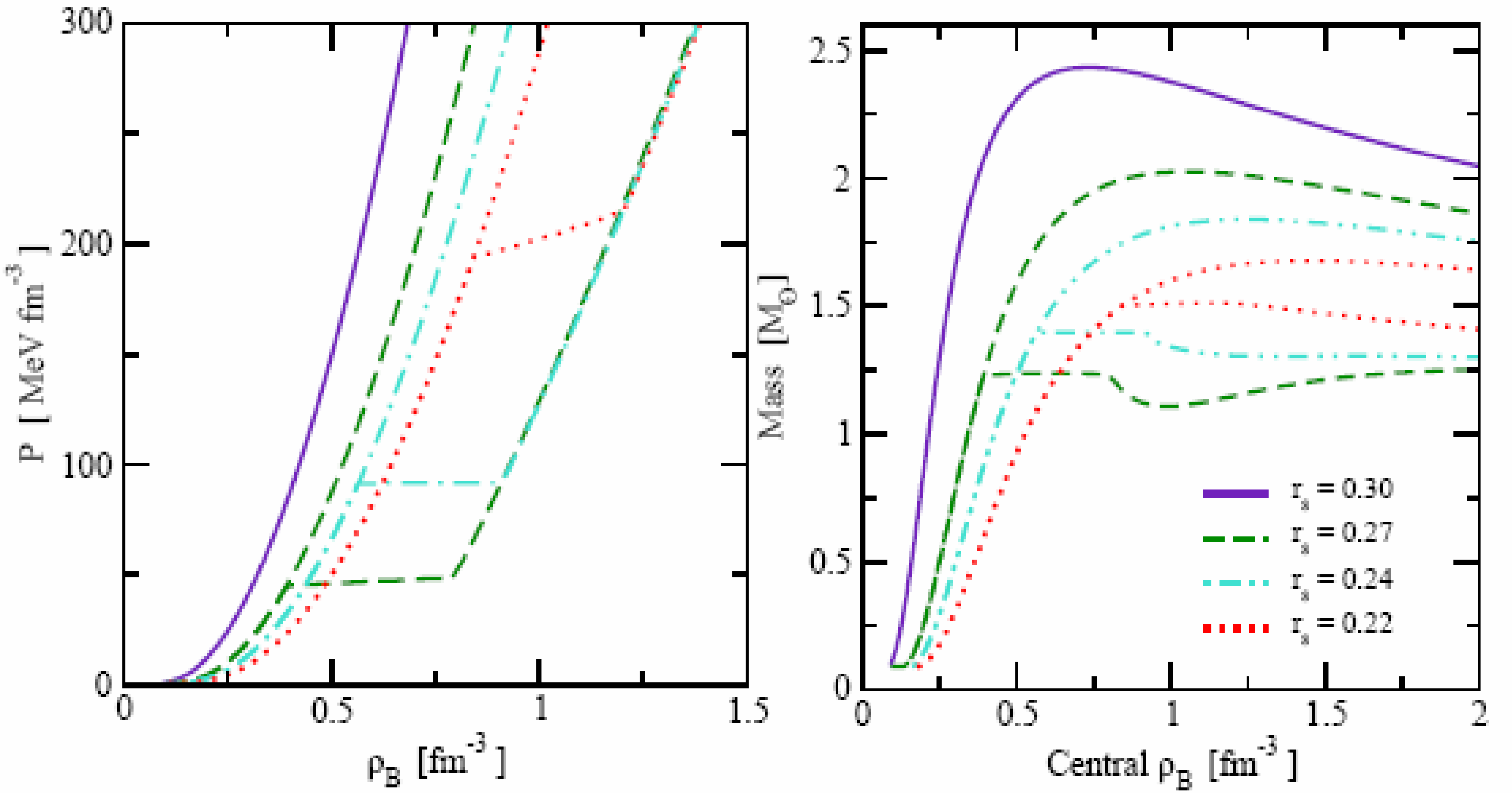
Cloet, Bentz, Thomas, Phys. Lett. B642 (2006) 210 (nucl-th/0605061)

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….

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

- Scalar polarizability also lowers mean scalar field strength

  - $M_N^* \sim 0.8\ M_N$ rather than $0.5\ M_N$ in QHD

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)

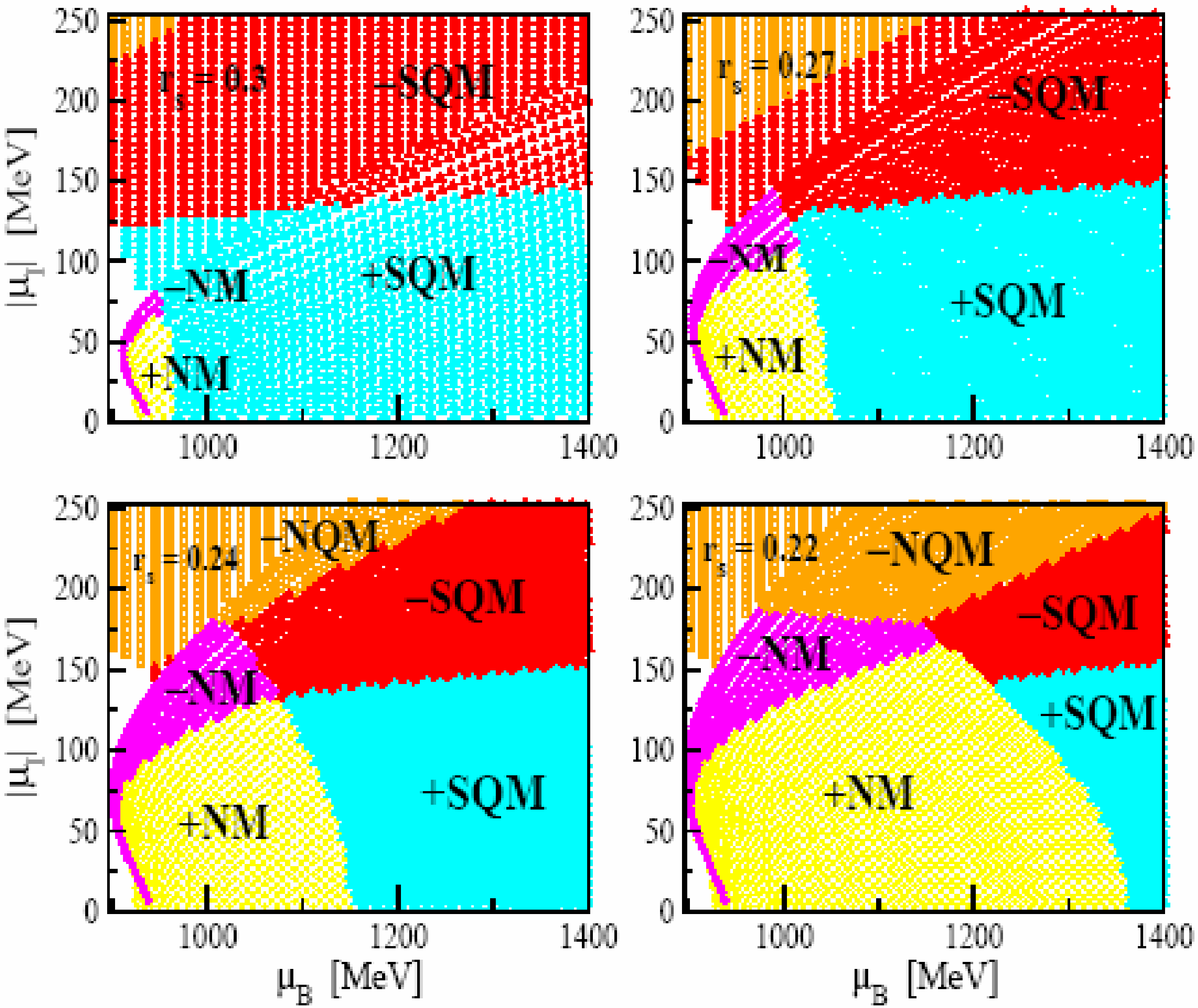
- Availability of realistic, density dependent Hyperon-N forces is essential for ρ > 2-3 ρ_0

- Covariant version can be tested experimentally – Jlab

- Already interesting results for NM, NQM, SQM in n stars

Special Mentions……

Phases of Dense Matter : NM (→ NQM) → SQM



Lawley, Bentz, AWT, nucl-th/0602014 (J Phys G32 (2006) 667)

Finite Hypernuclei with New QMC

	$^{16}_{\Lambda}$O (Expt.)	$^{17}_{\Lambda}$O	$^{17}_{\Sigma^-}$O	$^{17}_{\Sigma^0}$O	$^{17}_{\Sigma^+}$O	$^{17}_{\Xi^-}$O	$^{17}_{\Xi^0}$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	—

	$^{40}_{\Lambda}$Ca (Expt.)	$^{41}_{\Lambda}$Ca	$^{41}_{\Sigma^-}$Ca	$^{41}_{\Sigma^0}$Ca	$^{41}_{\Sigma^+}$Ca	$^{41}_{\Xi^-}$Ca	$^{41}_{\Xi^0}$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: Λ still well described**
- **Σ unbound or barely bound – this is a big improvement!**

Guichon, Matevosyan, Thomas, Tsushima, to appear

Quark Level Description of Finite Nuclei

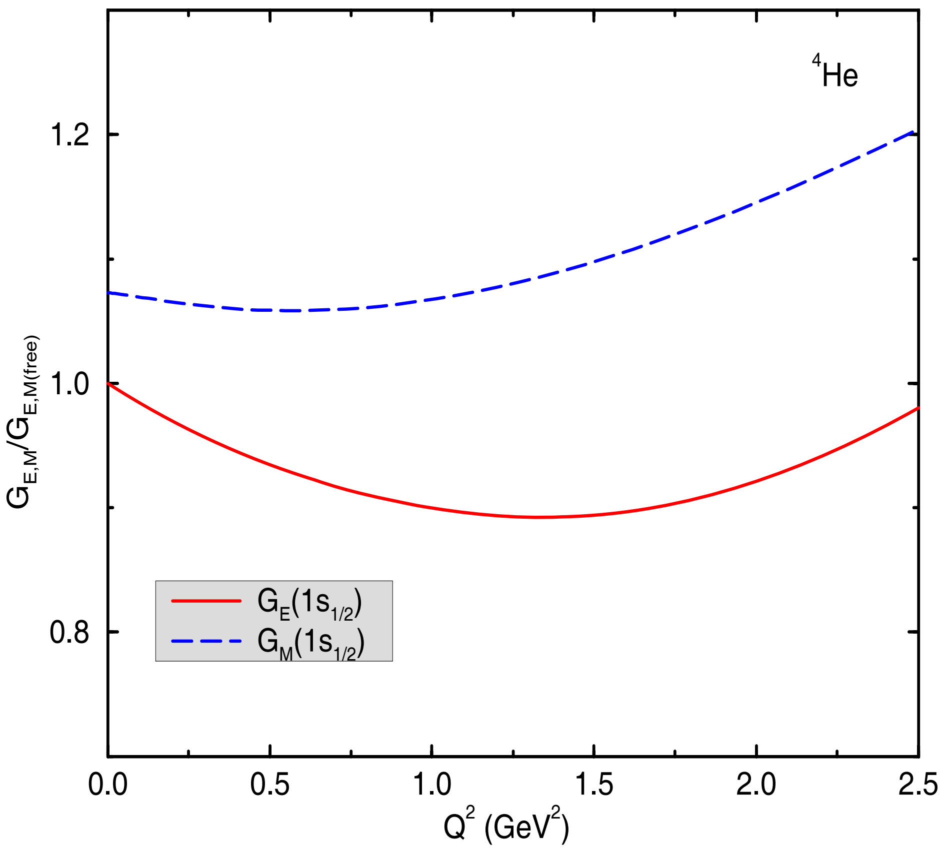
- **MAJOR CONCEPTUAL CHANGE:**
  What occupies shell model orbits are nucleon-like quasi-particles

- **Have: new mass, M_N^*;**
  new form factors, etc.

- **EXPERIMENTAL EVIDENCE?**

- **First have to ask the question!**

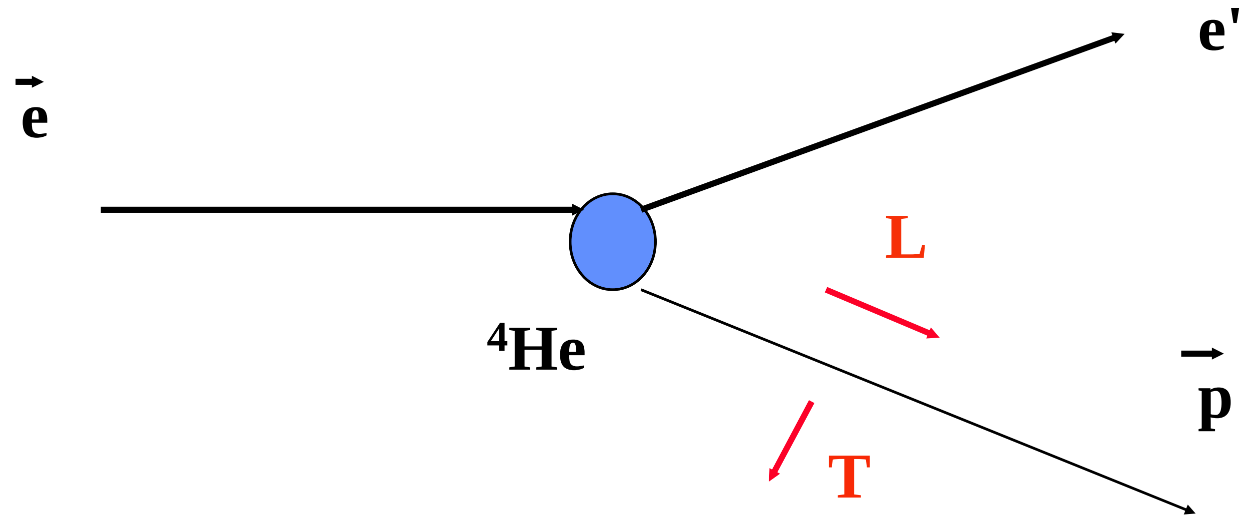
- **Changes are subtle…**



Lu *et al.*, Phys. Lett. B417 (1998) 217

Experimental Test of QMC at Mainz & JLab*

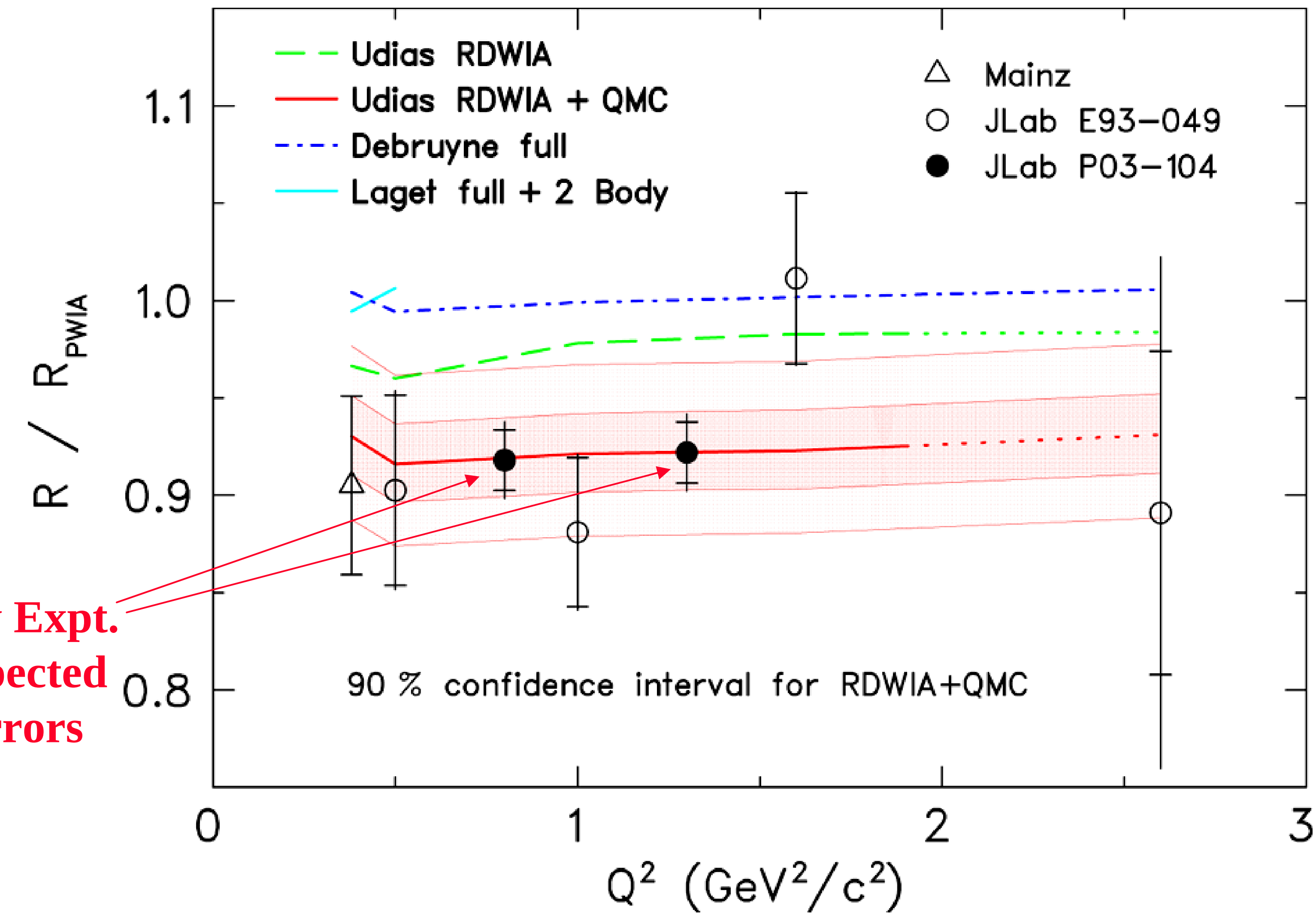
Capacity to measure polarization in coincidence:



$\sigma_T / \sigma_L \sim G_E/G_M$: Compare ratio in ^{4}He and in free space

S. Dieterich *et al.* , Phys. Lett. B500 (2001) 47; and JLab report 2002

Modification of the proton form factors in-medium



New Expt. Expected Errors

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

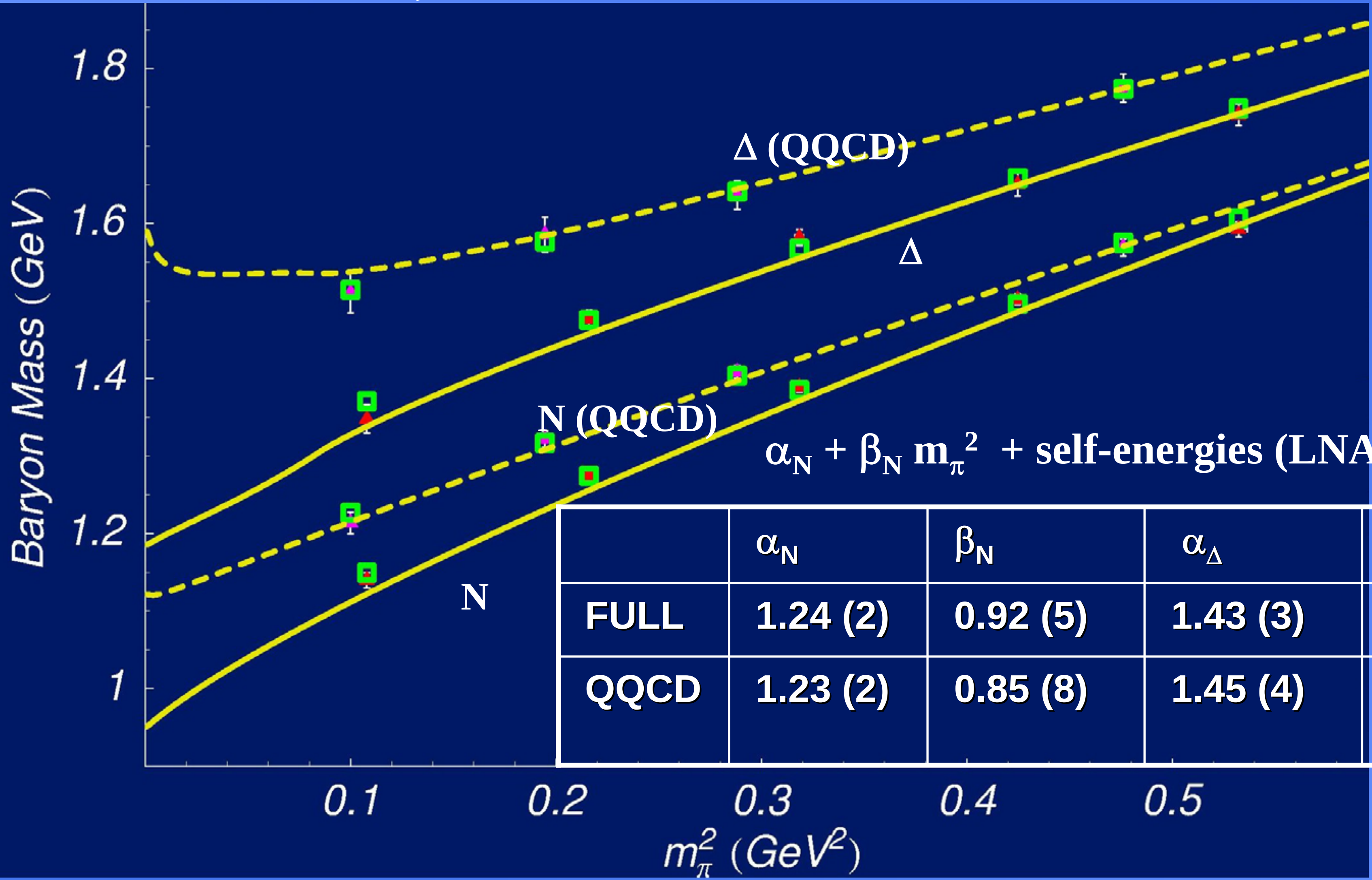
Can we Measure Scalar Polarizability in Lattice QCD ?

- 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

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

- Lattice data (from MILC Collaboration) : red triangles
- Green boxes: fit evaluating σ's on same finite grid as lattice
- Lines are exact, continuum results



$\alpha_N + \beta_N m_\pi^2$ + self-energies (LNA+NLNA)

	α_N	β_N	α_Δ	β_Δ
FULL	1.24 (2)	0.92 (5)	1.43 (3)	0.75 (8)
QQCD	1.23 (2)	0.85 (8)	1.45 (4)	0.71 (11)

Young *et al.*, hep-lat/0111041; Phys. Rev. D66 (2002) 094507

Variation of M_N under Chiral Invariant Scalar Field

i.e. Change m_q BUT not mass of pionic fluctuations

BUT study of chiral extrapolation of M_N and M_Δ (in QQCD and full QCD) can do this now !

$$M_N^* = a_0 + a_2\, m_\pi^2 + a_4\, m_\pi^4 + \text{self-energy}(m_\pi^{phys},\Lambda)$$

χ PT $\Rightarrow m_\pi^2 \approx 4\, m_q + 20\, m_q^2$, and in mean field $m_q \rightarrow m_q - g_\sigma^q\, \sigma$

positive

HENCE: $M_N^* = M_N - (4\, a_2\, g_\sigma^q)\, \sigma + (20\, a_2 + 16\, a_4)\, g_\sigma^{q\,2}\, \sigma^2$

$$\approx M_N - g_\sigma\, (1 - g_\sigma\, \sigma)\, \sigma$$

Coefficient ~ unity if units GeV $\Rightarrow$ 10-20% $\Downarrow$ at ρ_0 … as in QMC!