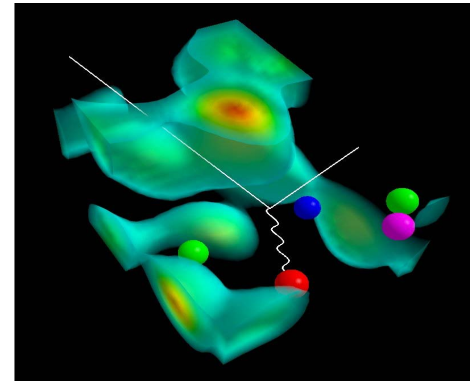
NUSYM13
July 22 – 26, 2013



Quark-Meson Coupling Model (QMC) and Nuclear Matter Constraints

J. R. Stone, University of Oxford/Tennessee/Maryland
D. L. Whittenbury, J. D. Carroll, A. W. Thomas and K. Tsushima
University of Adelaide and CSSM and ARC Centre of Excellence for Particle Physics at the Terascale

Problem:

Current models have limited predictive power – they have too many parameters and it is impossible to constrain them unambiguously

Models are often adjusted to fit only a selected class of data well, but they failure elsewhere is neglected . Such models cannot be right. Even "minimal" models are of a limited use in a broader context.

Suggested path towards a solution ?

Study carefully basic assumption of these models, their region of applicability, and the physics that justifies them

Narrowing down the number of models and their parameters, may increase the predictive power of the selected ones and move forward.

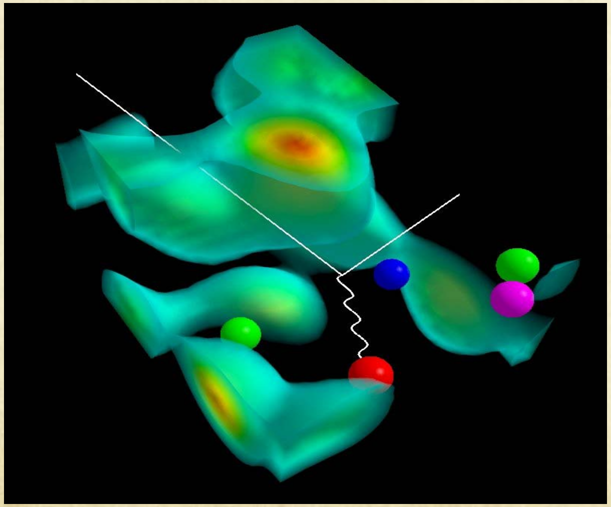
PHYSICS, AS WELL AS DATA, PROVIDES A GOOD GUIDANCE FOR SELECTING THEORIES.

Quark-Meson-Coupling Model

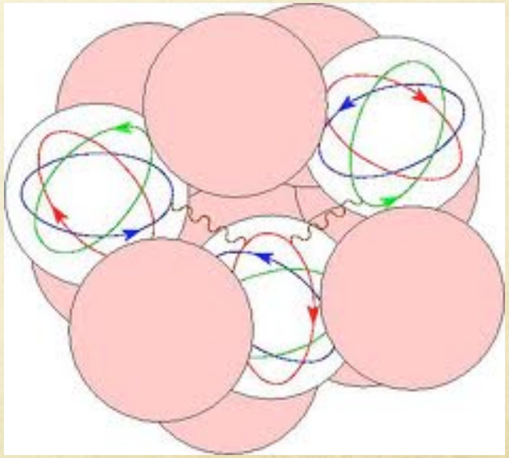
History:
Original: Pierre Guichon (Saclay), Tony Thomas (Adelaide) 1980'
Several variants developed in Japan, Europe, Brazil, Korea, China
Latest: Whittenbury et al. arXiv:1307.4166v1, July 2013

Main idea:

Effective model of the MEDIUM EFFECT on baryon structure and interactions
Quark level – coupling between u and d quarks of non-overlapping baryons by meson exchange - significantly simplifies as compared to nucleonic level.



QCD inspired *(Thomas)*



Schematic *(Guichon)*

WHAT WE DO:

(*For technical details see Whittenbury et al. arXiv:1307.4166v1*)

1. **Take a baryon in medium as an MIT bag (with one qluon exchange) immersed in a mean scalar field.**

2. **Self-consistently include the effects of local couplings of the u and d quarks to a scalar-isoscalar meson (σ) mean field, generated by all the other hadrons in the medium, on the internal structure of that hadron.**

3. **Calculate the effective mass of the baryon**

$$M_B^* = M_B - w_{\sigma B} g_{\sigma N} \bar{\sigma} + \frac{d}{2} \tilde{w}_{\sigma B} \left(g_{\sigma N} \bar{\sigma} \right)^2$$

where $g_{\sigma N}$ are CALCULATED coupling constants and $w_{\sigma B}$ are weighting factors allowing using unique σ-N coupling for other baryons. The modification of the internal baryon structure is the only place the quark degrees of freedom enter the model.

4. **Construct QMC Lagrangian on a hadronic level in the same way as in RMF but using the effective baryon mass M^*_B. and proceed to calculate standard observables.**

5. **Technically: Full Fock term is included (vector and tensor), and σ ω ρ π mesons**

Parameters (very little maneuvering space) :

meson-quark coupling constants:

$$g^q_\sigma,\ g^q_\omega,\ \text{and}\ g^q_\rho\ \text{for}\ q = u, d\ (g^s_\alpha = 0\ \text{for all mesons}\ \alpha).$$

Fixed to saturation density 0.16 fm^{-3}, binding energy of SNM -16 MeV and the symmetry energy 32.5 MeV

Meson masses: ω, ρ, π keep their physical values
σ = 700 MeV

Cut-off parameter Λ (in form-factors in the exchange terms)
constrained between 0.9 and 1.3 GeV

Free nucleon radius: 1 fm (limited sensitivity within change +/- 20%)

All other parameters either calculated or fixed by symmetry.

WHAT WE GET:

1. Model formulated on quark level which can tackle fundamental issues of nuclear structure within QCD that cannot be addressed by low-energy nuclear theory alone.

2. Scalar polarizability of the baryon:

$$M_B^* = M_B - g_{\sigma B}\sigma + \frac{d}{2}\left(g_{\sigma B}\sigma\right)^2$$

Atoms: re-arrangement to oppose the effect of external field – polarization

Nucleons: self-consistent response to the applied mean scalar field tends to oppose that applied field.
Increase in the scalar field effectively decreases coupling of the σ to an in-medium baryon → the baryons are source of of the scalar field → saturation (equilibrium) will be reached.

NATURAL EXPLANATION FOR SATURATION OF NUCLEAR MATTER

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 chiral invariant 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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A. W. Thomas, Prog.Theor.Phys.Suppl.156:124-136,2004

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Results I. Nucleonic matter

Model	$^{\dagger}S_0$	L	K_{sym}	K_0	Q_0	$K_{\tau,v}$
Standard	32.5	101	66	298	-189	-477
$\Lambda = 1.0$	32.5	106	94	305	-141	-492
$\Lambda = 1.1$	32.5	111	128	312	-85	-509
$\Lambda = 1.2$	32.5	117	166	319	-19	-530
$\Lambda = 1.3$	32.5	124	211	329	64	-560
$R = 0.8$	32.5	110	120	300	-142	-485

Standard: Λ =0.9 GeV, R = 1 fm

$$E_{\mathrm{SNM}}(\rho) = E_{\mathrm{o}} + \frac{1}{2}K_{\mathrm{o}}x^2 + \frac{1}{6}Q_{\mathrm{o}}x^3 + O(x^4),$$

$$K_{\tau,v} = \left(K_{\mathrm{sym}} - 6L - \frac{Q_{\mathrm{o}}}{K_{\mathrm{o}}}L\right),$$

$$\mathcal{S} = J + Lx + \frac{1}{2}K_{\mathrm{sym}}x^2 + \frac{1}{6}Q_{\mathrm{sym}}x^3 + O(x^4).$$

Hyperons

P. A. M. Guichon, A. W. Thomas and K. Tsushima, Nucl. Phys. A 814, 66 (2008).

- 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!

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Λ and Ξ hypernuclei in QMC:

P. A. M. Guichon, A. W. Thomas and K. Tsushima, Nucl. Phys. A 814, 66 (2008).

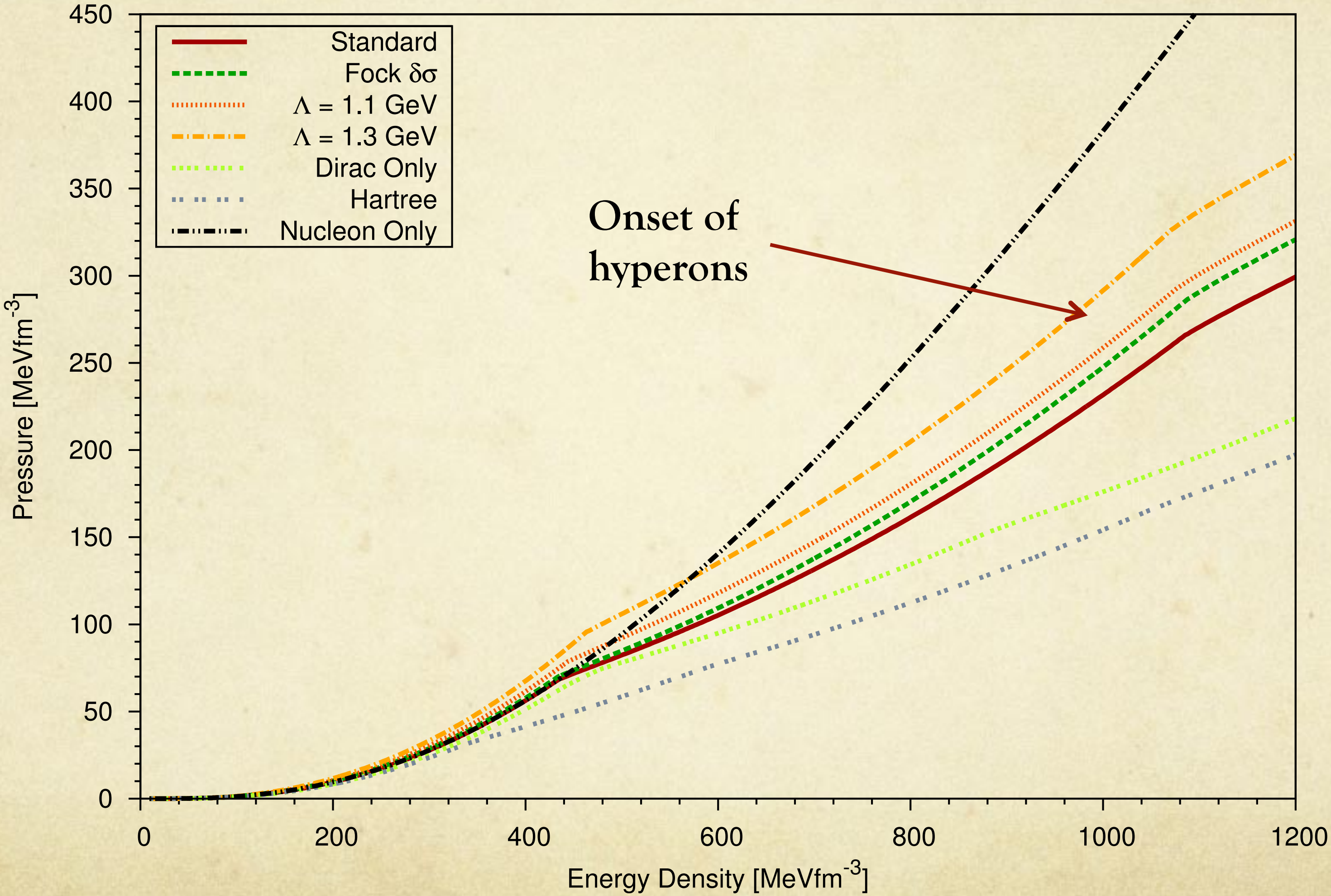
Calculation without additional parameters

	$^{89}_{\Lambda}$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

Predicts Ξ bound by 10 – 15 MeV (to be tested in JPARC)

Increasing split between Λ and Ξ masses with increasing density.

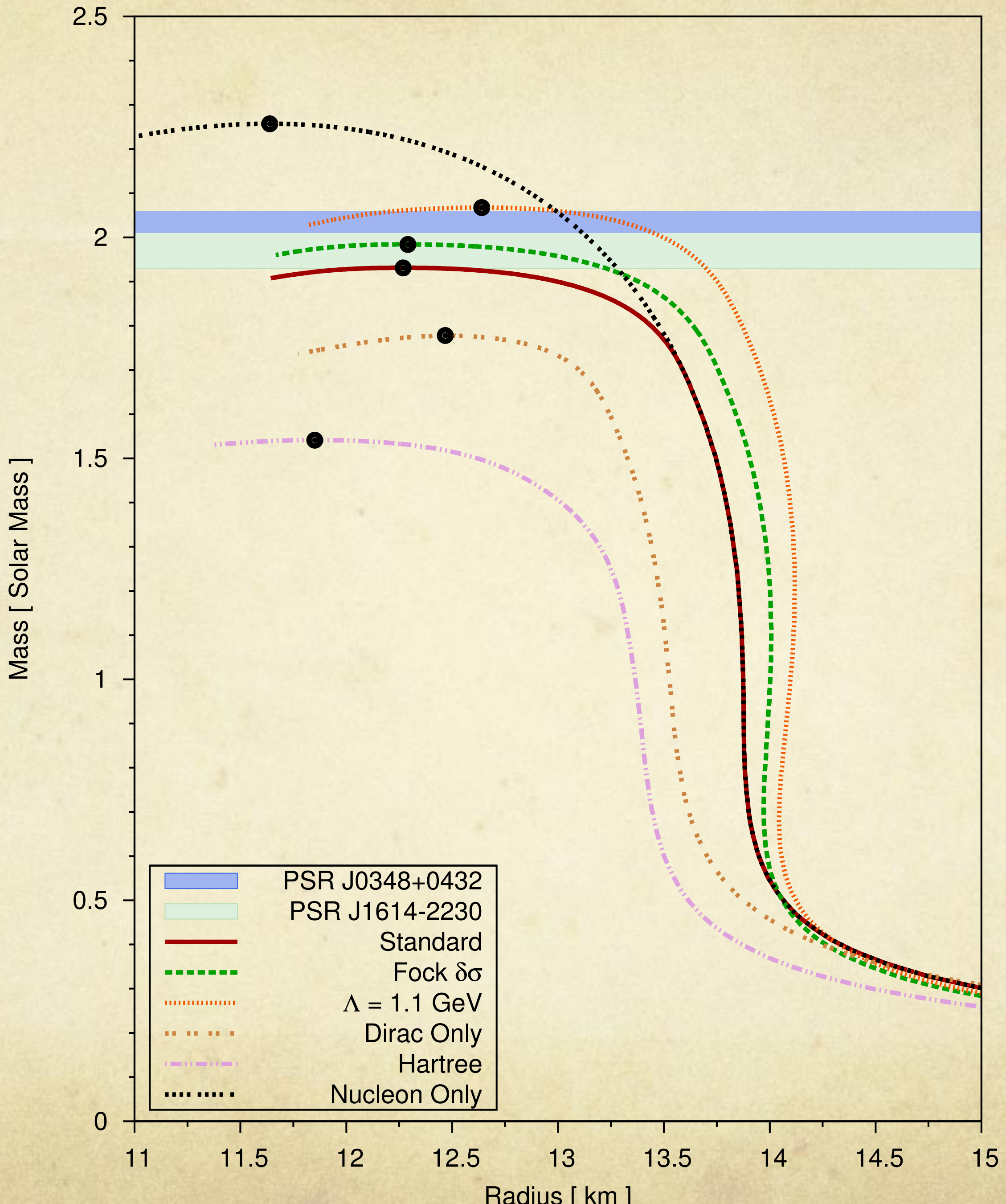
Pressure as a function of energy density as predicted by QMC with hyperons



Results II: Cold neutron star

Model	$g_{\sigma N}$	$g_{\omega N}$	g_{ρ}	K_0 (MeV)	L (MeV)	R (km)	$M_{\max}$ ($M_{\odot}$)	$\rho_c^{\max}$ (ρ_0)
Standard	10.42	11.02	4.55	298	101	12.27	1.93	5.52
$\Lambda = 1.0$	10.74	11.66	4.68	305	106	12.45	2.00	5.32
$\Lambda = 1.1$	11.10	12.33	4.84	312	111	12.64	2.07	5.12
$\Lambda = 1.2$	11.49	13.06	5.03	319	117	12.83	2.14	4.92
$\Lambda = 1.3$	11.93	13.85	5.24	329	124	13.02	2.23	4.74
$R = 0.8$	11.20	12.01	4.52	300	110	12.41	1.98	5.38

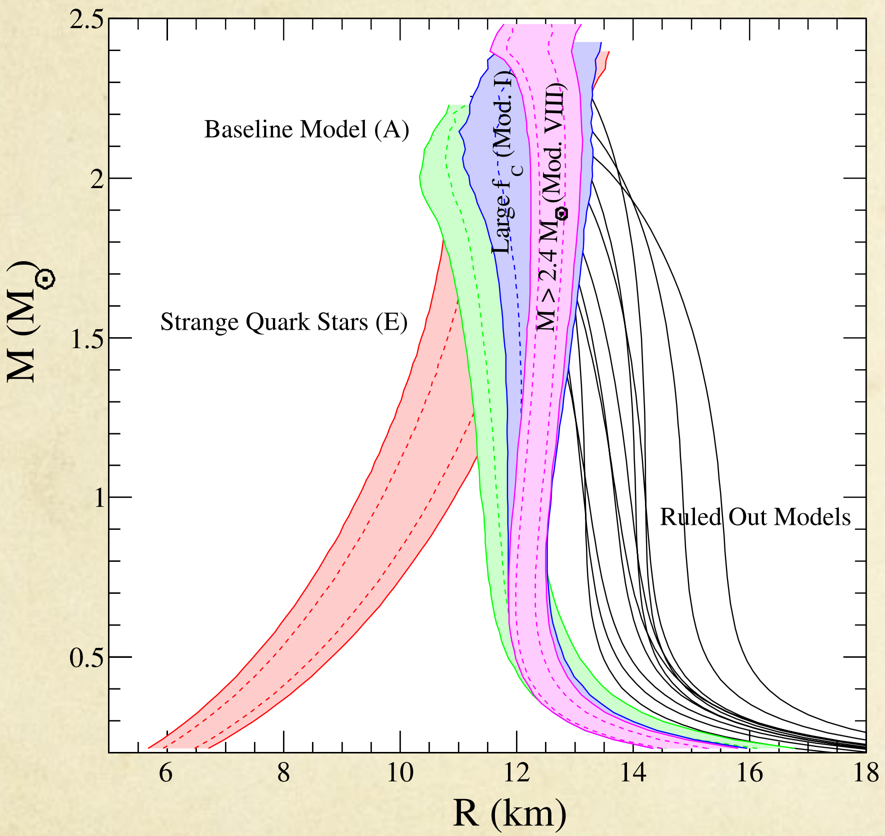
Stone, Stone and Moszkowski: Under review in PRC: 250 < K_0 < 315 MeV



Antoniadis et al.
Demorest et al.

Steiner, Lattimer and Brown

THE ASTROPHYSICAL JOURNAL LETTERS, 765:L5 (5pp), 2013 March 1



Mass : 2.1 solar masses

95% confidence:

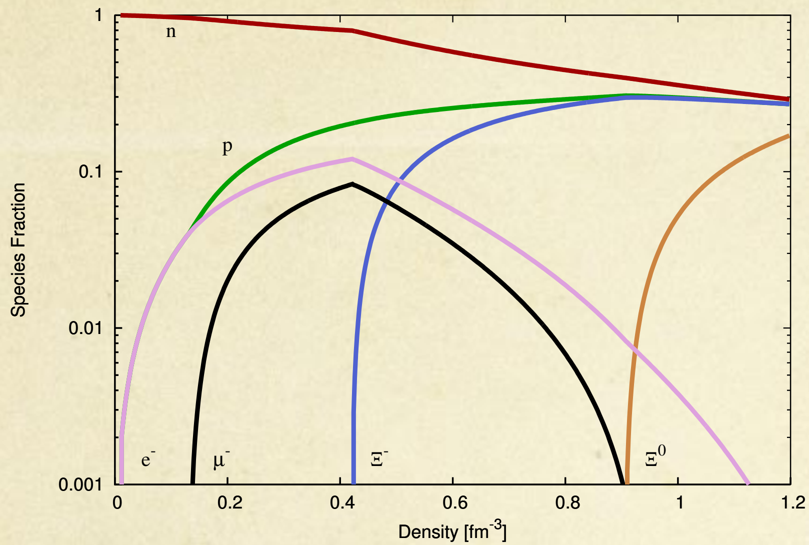
Lower limit on the radius:

10.17 km

Upper limit on the radius

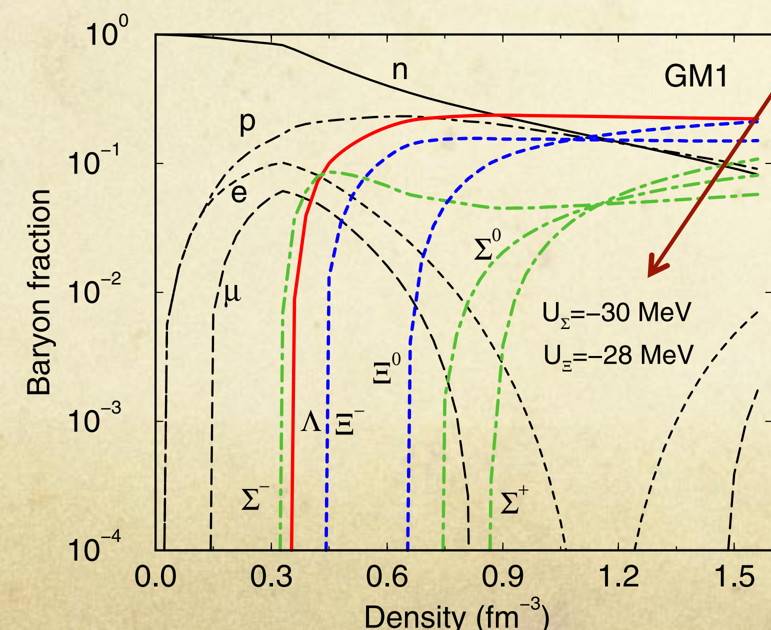
13.29 km

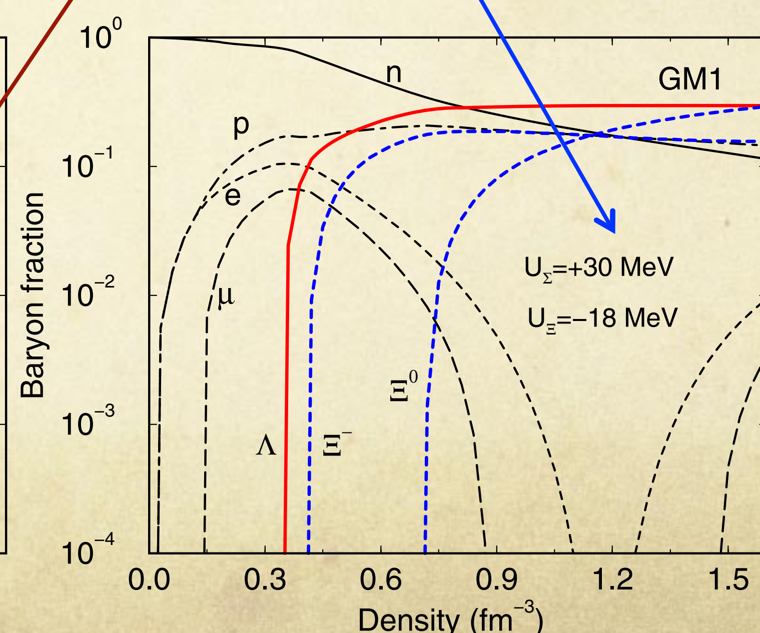
QMC predicted composition of HD matter (Y-N potentials calculated)



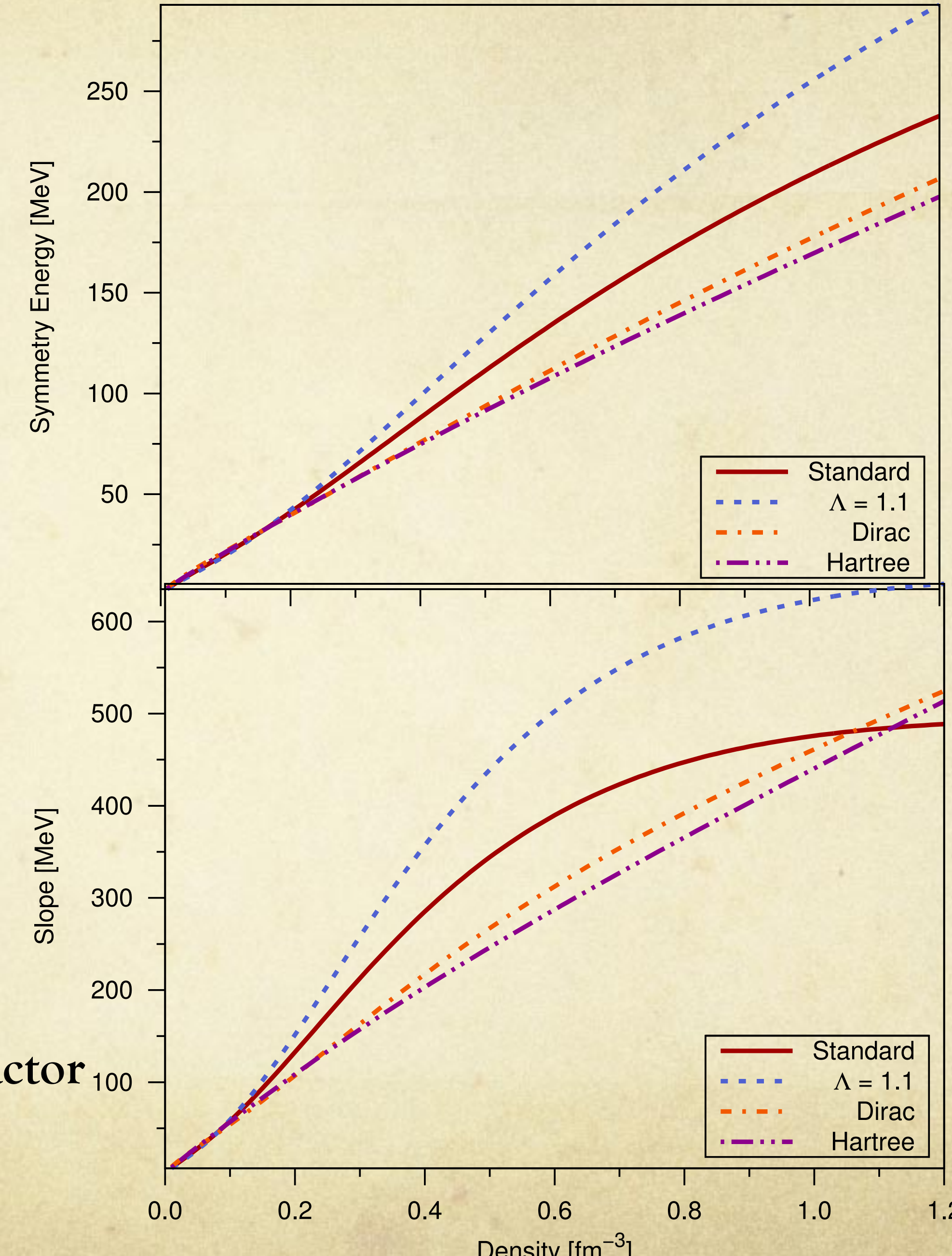
RMF with GM1 interaction empirical Y-N potentials fitted selfconsistently to data

J. Schaeffner-Bielich, NPA 835, 279 (2010)





Symmetry energy S (top) and its slope L (bottom) as a function of baryon number density as calculated in QMC.



Effect of the Fock term:

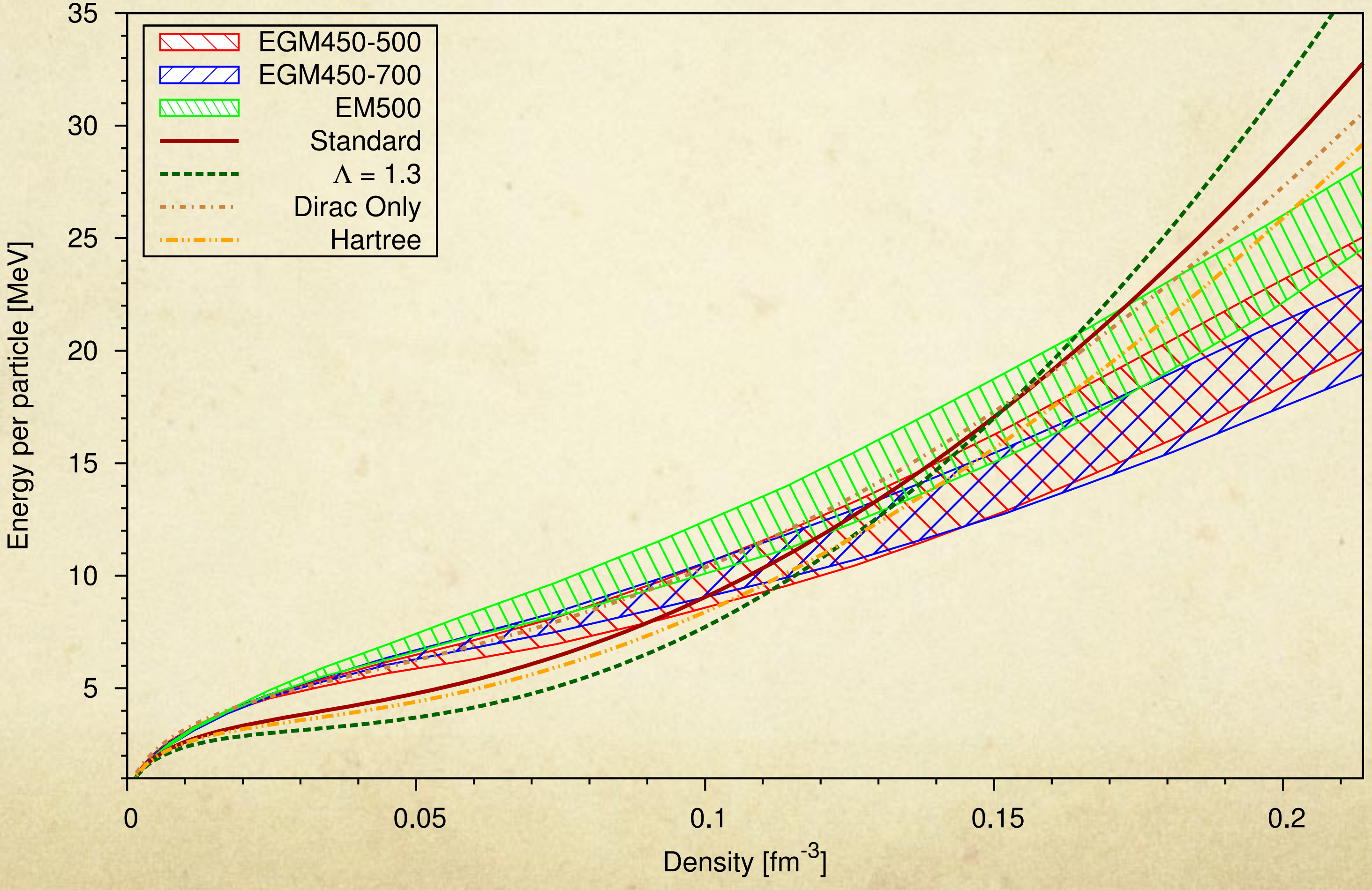
Standard: vector + tensor

Dirac: vector

Hartree: no Fock term

Λ cut-off parameter of the form-factor in the Fock term.

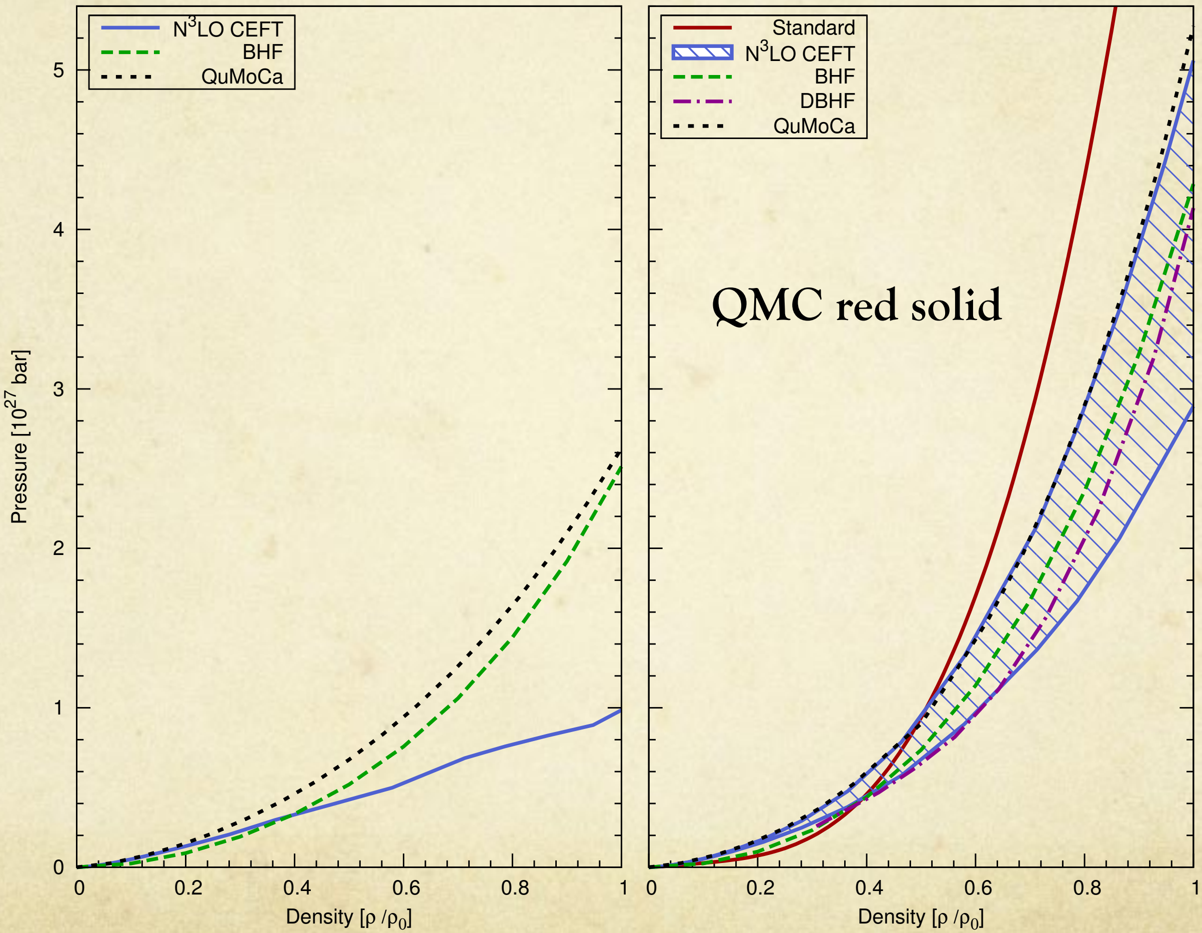
Pure neutron matter energy per particle as a function of density as obtained in QMC, in comparison with complete CEFT at N^{3}LO order for more details of the latter see: *I. Tews, T. Krueger, K. Hebeler and A. Schwenk, Phys. Rev. Lett. 110 (2013) 032504*



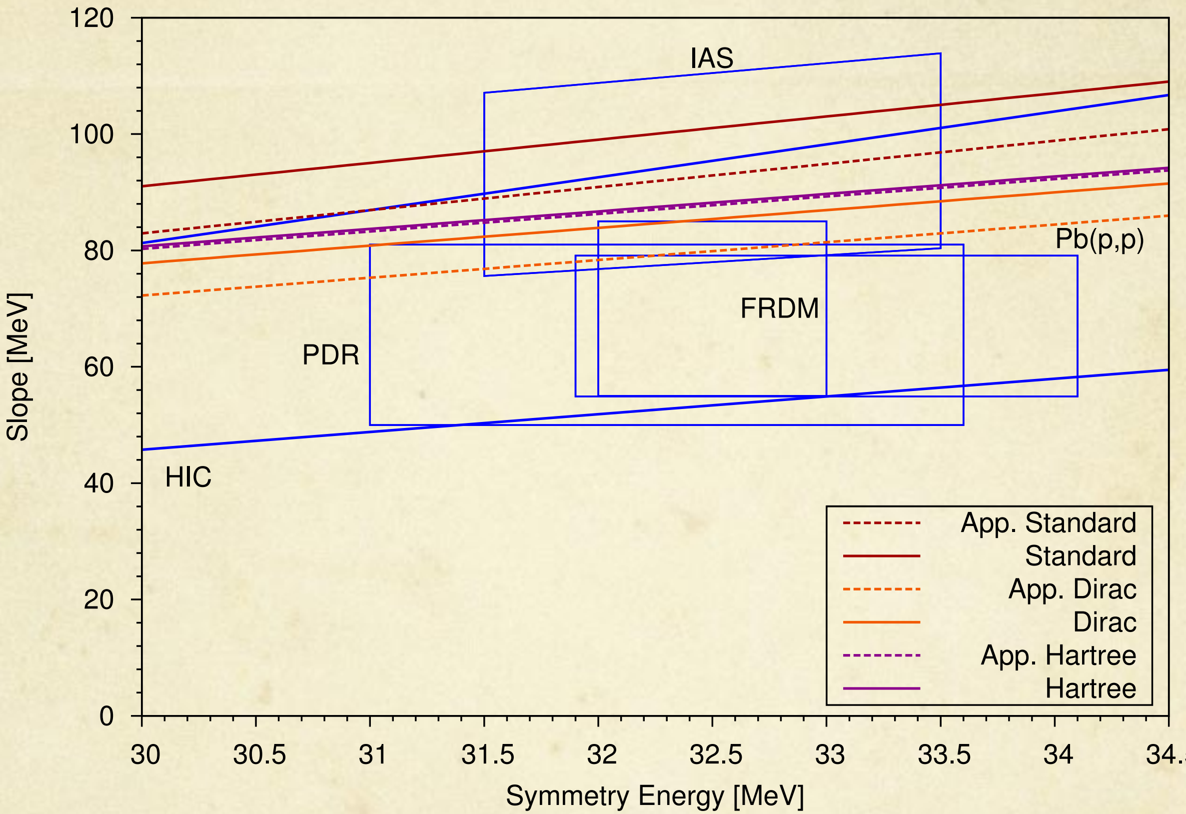
Pressure in pure neutron matter as calculated in different models

Left panel: without 3BF **Right panel: the same but with 3BF.**

DBHF added in right panel [Tsang et al., PRC 86, 015803 (2012)]



Updated constraints Tsang et al., PRC 86, 015803 (2012)



$$\mathcal{S}(\rho) = \frac{1}{2}\frac{\partial^2 E}{\partial \beta^2}\Big|_{\rho,\beta=0},$$

$$E = \epsilon_{\text{hadronic}}/\rho,$$

"App" $$S(\rho) = \mathcal{E}(\rho, \beta=1) - \mathcal{E}(\rho,\beta=0)\ ,$$

$$\mathcal{E} = \frac{1}{\rho}\left(\epsilon_{\text{hadronic}} - \sum_B M_B \rho_B\right)$$

Application to finite nuclei:

Guichon, Matevosyan, Sandulescu, Thomas, NPA 772, 1, 2006

Density dependent force in a non-relativistic approximation can be derived form QMC. The Hamiltonian depends on QMC coupling constants and polarizability d but has formally similar structure to the Skyrme forces.

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

highlights
scalar polarizability

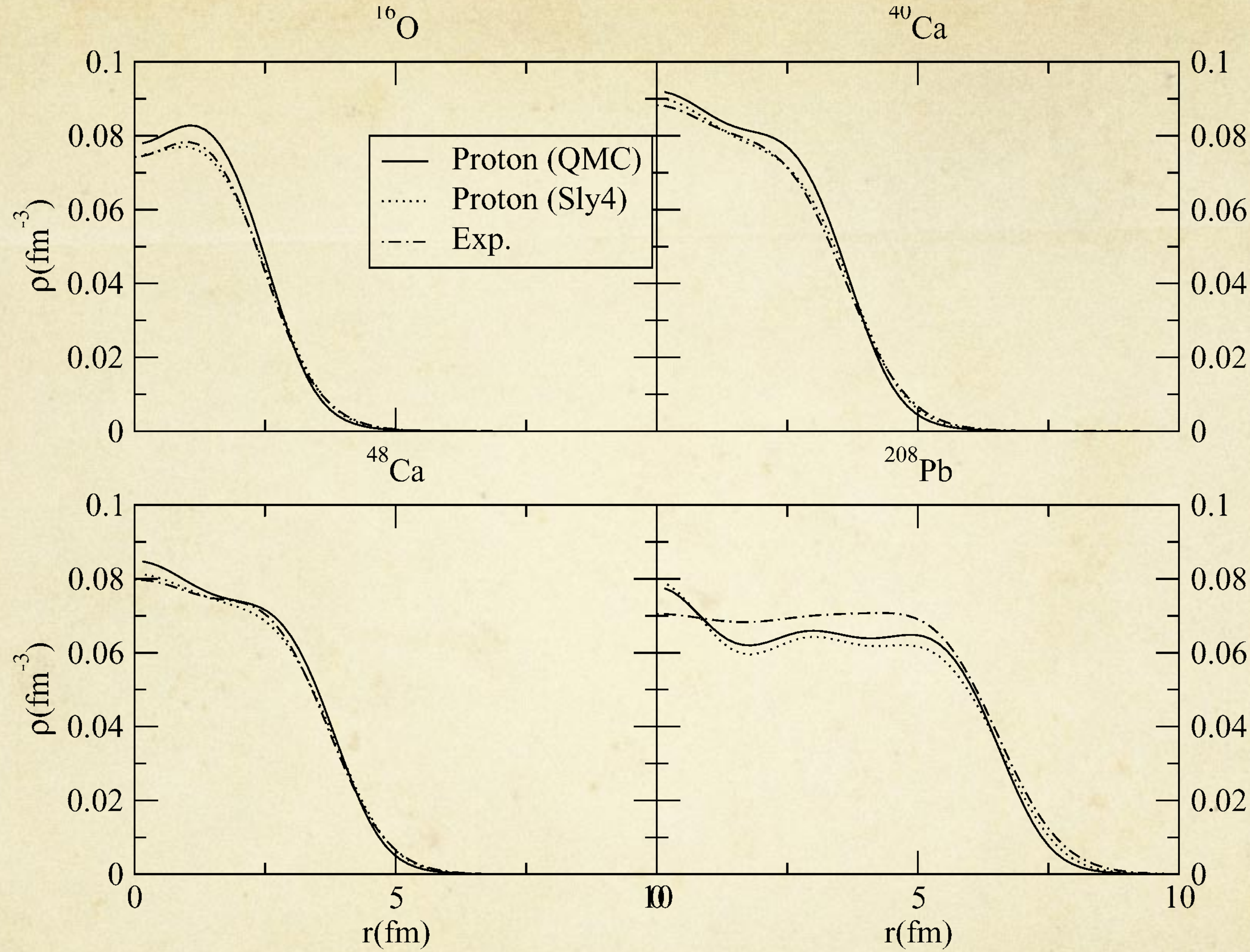
Guichon, Matevosyan, Sandulescu, Thomas, NPA 772, (2006)

Table 3
Binding energy and radii calculated in QMC-HF, as described in the text

	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

Table 4
Comparison between the QMC and "experimental" spin–orbit splittings. Because the experimental splittings are no so well known in the case of ^{48}Ca and ^{208}Pb, we give the values corresponding to the Skyrme Sly4 prediction

	Neutrons (exp)	Neutrons (QMC)	Protons (exp)	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	6.00	6.24
^{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



QMC proton density distribution compared with experiment and Skyrme SLy4

SUMMARY

QMC has a natural explanation for saturation of nuclear matter and in-medium effects through many-body forces

It is not limited to nucleons but can be applied to hyperons and CALCULATE interaction of any hadron in nuclear medium with NO ADDITIONAL parameters.

Yields effective, density dependent Λ N, Σ N, Ξ N forces (not yet published) with NO additional parameters – reproduces known properties of hypernuclei

Can be used to derive density-dependent effective force such as the Skyrme force which performs well in finite nuclei (HF+BCS QMC code for axially symmetric nuclei has been just developed and is in a testing stage (with P. - G. Reinhard)

BUT

IF QMC is as valid as we believe, it has to yield predictions consistent with results in other areas of nuclear physics and astrophysics

FUTURE: EoS for supernova matter (Chikako Ishizuka, Akira Ohnishi)
(QMC at finite temperature)

Statistical analysis of mass and radii of NS (Andrew Steiner)

Projected shell model (Yang Sun)

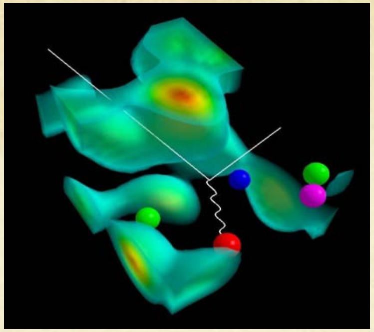
Ab-initio calculation of light nuclei (Emiko Hiyama)

Rotating neutron stars (Fridolin Weber + collaborators)

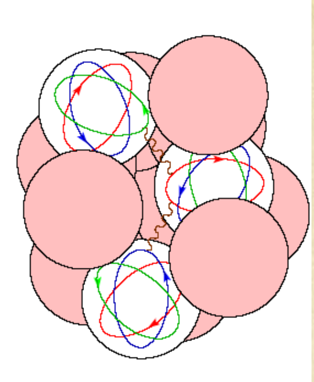
\+ + +

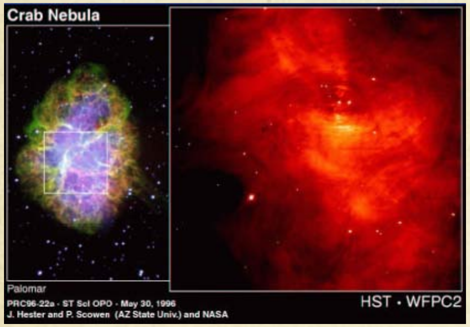
SUGGESTIONS WELCOME

N,Λ, Ξ, ω, D, J/Ψ in nuclear matter



QCD & hadron structure

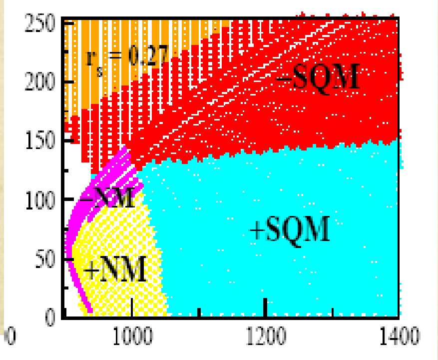




n star

∞ nuclear matter

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



quark matter

Structure of finite nuclei & hypernuclei

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