QMC and the nature of dense matter:

Written in the stars?

J. D. Carroll

(CSSM, University of Adelaide)

Achievements and New Directions in Subatomic Physics: Workshop in Honour of Tony Thomas' 60th Birthday, 2010

Anthony W Thomas

Anthony W Thomas

Anthony W Thomas

Anthony W Thomas

Anthony W Thomas

Outline

1. The Basics:
   - The Nature of Dense Matter
   - The Models
2. Simulations:
   - Hadronic Matter
   - Mixed-Phase Matter

Motivation

We wish to understand the properties of matter over a wide range of densities; from single atomic nuclei to neutron stars.

In order to do this, we must first understand the fundamental and effective degrees of freedom at each density scale.

In order to evaluate success, we need to compare predictions over a wide range of density scales to observable phenomena.

Motivation

We wish to understand the properties of matter over a wide range of densities; from single atomic nuclei to neutron stars.

In order to do this, we must first understand the fundamental and effective degrees of freedom at each density scale.

In order to evaluate success, we need to compare predictions over a wide range of density scales to observable phenomena.

Motivation

We wish to understand the properties of matter over a wide range of densities; from single atomic nuclei to neutron stars.

In order to do this, we must first understand the fundamental and effective degrees of freedom at each density scale.

In order to evaluate success, we need to compare predictions over a wide range of density scales to observable phenomena.

Motivation

We wish to understand the properties of matter over a wide range of densities; from single atomic nuclei to neutron stars.

In order to do this, we must first understand the fundamental and effective degrees of freedom at each density scale.

In order to evaluate success, we need to compare predictions over a wide range of density scales to observable phenomena.

Motivation

We wish to understand the properties of matter over a wide range of densities; from single atomic nuclei to neutron stars.

In order to do this, we must first understand the fundamental and effective degrees of freedom at each density scale.

In order to evaluate success, we need to compare predictions over a wide range of density scales to observable phenomena.

Motivation

We wish to understand the properties of matter over a wide range of densities; from single atomic nuclei to neutron stars.

In order to do this, we must first understand the fundamental and effective degrees of freedom at each density scale.

In order to evaluate success, we need to compare predictions over a wide range of density scales to observable phenomena.

What We Know

What we know:

- Quarks and Gluons are the fundamental degrees of freedom
- At low densities, Baryons (Nucleons) are the effective degrees of freedom
- At high densities...

What We Know

What we know:

- Quarks and Gluons are the fundamental degrees of freedom
- At low densities, Baryons (Nucleons) are the effective degrees of freedom
- At high densities...

What We Know

What we know:

- Quarks and Gluons are the fundamental degrees of freedom
- At low densities, Baryons (Nucleons) are the effective degrees of freedom
- At high densities...

What We Know

What we know:

- Quarks and Gluons are the fundamental degrees of freedom
- At low densities, Baryons (Nucleons) are the effective degrees of freedom
- At high densities...

What We Know

What we know:

- Quarks and Gluons are the fundamental degrees of freedom
- At low densities, Baryons (Nucleons) are the effective degrees of freedom
- At high densities... ???

What We Know

What we know:

- Quarks and Gluons are the fundamental degrees of freedom
- At low densities, Baryons (Nucleons) are the effective degrees of freedom
- At high densities... ???

What We Know

What we know:

- Quarks and Gluons are the fundamental degrees of freedom
- At low densities, Baryons (Nucleons) are the effective degrees of freedom
- At high densities... ??? = Hyperons? Quarks? Other?

Hadronic Models
A Brief Overview

Quantum HadroDynamics (QHD) Model

- Simple description of nucleons immersed in mean-field σ, ω, and ρ potentials,
- Constructed at the baryon level,
- Issues with large scalar potentials causing negative effective masses.

Quark-Meson Coupling (QMC) Model

- Similar final form as QHD, but with self-consistent response to the σ field, despite construction from quark level,
- Better predictions for bulk properties of dense matter,
- No issues with negative effective masses.

Hadronic Models
A Brief Overview

Quantum **H**adro**D**ynamics (**QHD**) Model

- Simple description of nucleons immersed in mean-field σ, ω, and ρ potentials,
- Constructed at the baryon level,
- Issues with large scalar potentials causing negative effective masses.

Quark-**M**eson **C**oupling (**QMC**) Model

- Similar final form as QHD, but with self-consistent response to the σ field, despite construction from quark level,
- Better predictions for bulk properties of dense matter,
- No issues with negative effective masses.

Hadronic Models
A Brief Overview

Quantum **H**adro**D**ynamics (**QHD**) Model

- Simple description of nucleons immersed in mean-field σ, ω, and ρ potentials,
- Constructed at the baryon level,
- Issues with large scalar potentials causing negative effective masses.

Quark-**M**eson **C**oupling (**QMC**) Model

- Similar final form as QHD, but with self-consistent response to the σ field, despite construction from quark level,
- Better predictions for bulk properties of dense matter,
- No issues with negative effective masses.

Hadronic Models
A Brief Overview

Quantum **H**adro**D**ynamics (**QHD**) Model

- Simple description of nucleons immersed in mean-field σ, ω, and ρ potentials,
- Constructed at the baryon level,
- Issues with large scalar potentials causing negative effective masses.

Quark-**M**eson **C**oupling (**QMC**) Model

- Similar final form as QHD, but with self-consistent response to the σ field, despite construction from quark level,
- Better predictions for bulk properties of dense matter,
- No issues with negative effective masses.

Hadronic Models
A Brief Overview

Quantum **H**adro**D**ynamics (**QHD**) Model

QHD:

$$M_B^* = M_B + \Sigma_B^s = M_B - g_{\sigma B}\langle\sigma\rangle$$

Quark-**M**eson **C**oupling (**QMC**) Model

- Similar final form as QHD, but with self-consistent response to the σ field, despite construction from quark level,
- Better predictions for bulk properties of dense matter,
- No issues with negative effective masses.

Hadronic Models
A Brief Overview

Quantum **H**adro**D**ynamics (**QHD**) Model

QHD:

$$M_B^* = M_B + \Sigma_B^s = M_B - g_{\sigma B}\langle\sigma\rangle$$

Quark-**M**eson **C**oupling (**QMC**) Model

- Similar final form as QHD, but with self-consistent response to the σ field, despite construction from quark level,
- Better predictions for bulk properties of dense matter,
- No issues with negative effective masses.

Hadronic Models
A Brief Overview

Quantum **H**adro**D**ynamics (**QHD**) Model

QHD:

$$M_B^* = M_B + \Sigma_B^s = M_B - g_{\sigma B}\langle\sigma\rangle$$

Quark-**M**eson **C**oupling (**QMC**) Model

- Similar final form as QHD, but with self-consistent response to the σ field, despite construction from quark level,
- Better predictions for bulk properties of dense matter,
- No issues with negative effective masses.

Hadronic Models
A Brief Overview

Quantum **H**adro**D**ynamics (**QHD**) Model

QHD:

$$M_B^* = M_B + \Sigma_B^s = M_B - g_{\sigma B}\langle\sigma\rangle$$

Quark-**M**eson **C**oupling (**QMC**) Model

- Similar final form as QHD, but with self-consistent response to the σ field, despite construction from quark level,
- Better predictions for bulk properties of dense matter,
- No issues with negative effective masses.

Hadronic Models
A Brief Overview

Quantum **H**adro**D**ynamics (**QHD**) Model

QHD:

$$M_B^* = M_B + \Sigma_B^s = M_B - g_{\sigma B}\langle\sigma\rangle$$

Quark-**M**eson **C**oupling (**QMC**) Model

QMC:

$$M_B^* = M_B + \Sigma_B^s = M_B - w_B^s g_{\sigma N}\langle\sigma\rangle + \frac{d}{2}\tilde{w}_B^s\left(g_{\sigma N}\langle\sigma\rangle\right)^2$$

Hadronic Models
A Brief Overview

Quantum **H**adro**D**ynamics (**QHD**) Model

QHD:

$$M_B^* = M_B + \Sigma_B^s = M_B - g_{\sigma B} \langle \sigma \rangle$$

Quark-**M**eson **C**oupling (**QMC**) Model

QMC:

$$M_B^* = M_B + \Sigma_B^s = M_B - w_B^s g_{\sigma N} \langle \sigma \rangle + \frac{d}{2} \tilde{w}_B^s \left(g_{\sigma N} \langle \sigma \rangle \right)^2$$

Hadronic Models

A Brief Overview

Quantum **H**adro**D**ynamics (**QHD**) Model

QHD:

$$M_B^* = M_B + \Sigma_B^s = M_B - g_{\sigma B}\langle\sigma\rangle$$

Quark-**M**eson **C**oupling (**QMC**) Model

QMC:

$$M_B^* = M_B + \Sigma_B^s = M_B - w_B^s g_{\sigma N}\langle\sigma\rangle + \frac{d}{2}\tilde{w}_B^s \left(g_{\sigma N}\langle\sigma\rangle\right)^2$$

Hadronic Models

A Brief Overview

Quantum **H**adro**D**ynamics (**QHD**) Model

QHD:

$$M_B^* = M_B + \Sigma_B^s = M_B - g_{\sigma B}\langle\sigma\rangle$$

Quark-**M**eson **C**oupling (**QMC**) Model

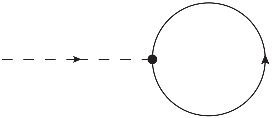
QMC:

↙ $\kappa_{\rm NS}$ in GC's talk

$$M_B^* = M_B + \Sigma_B^s = M_B - w_B^s g_{\sigma N}\langle\sigma\rangle + \frac{d}{2}\tilde{w}_B^s\left(g_{\sigma N}\langle\sigma\rangle\right)^2$$

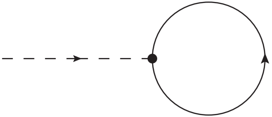
Hadronic Models
A Brief Overview

In QHD, at Hartree level (mean-field), the scalar self-energy involves only the tadpole term:



Hadronic Models
A Brief Overview

In QHD, at Hartree level (mean-field), the scalar self-energy involves only the tadpole term:

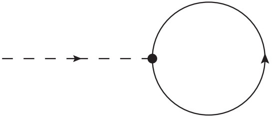


Hartree Σ_B^s (QHD)

$$\begin{aligned}\Sigma_B^s &= -g_{\sigma B}\langle\sigma\rangle \\ &= -g_{\sigma B}\sum_{B'}\frac{g_{\sigma B'}}{m_\sigma^2}\frac{(2J_{B'}+1)}{(2\pi)^3}M_{B'}^*\int\frac{\theta(k_{F_{B'}}-|\vec{k}|)\,d^3k}{\sqrt{\vec{k}^2+M_{B'}^{*2}}}\end{aligned}$$

Hadronic Models
A Brief Overview

In QHD, at Hartree level (mean-field), the scalar self-energy involves only the tadpole term:

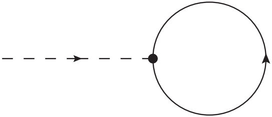


Hartree Σ_B^s (QHD)

$$\begin{aligned}\Sigma_B^s &= -g_{\sigma B}\langle\sigma\rangle \\ &= -g_{\sigma B}\sum_{B'}\frac{g_{\sigma B'}}{m_\sigma^2}\frac{(2J_{B'}+1)}{(2\pi)^3}M^*_{B'}\int\frac{\theta(k_{F_{B'}}-|\vec{k}|)\,d^3k}{\sqrt{\vec{k}^2+M^{*2}_{B'}}}\end{aligned}$$

Hadronic Models
A Brief Overview

In QHD, at Hartree level (mean-field), the scalar self-energy involves only the tadpole term:



Hartree Σ_B^s (QHD)

$$\begin{aligned}\Sigma_B^s &= -g_{\sigma B}\langle\sigma\rangle \\ &= -g_{\sigma B}\sum_{B'}\frac{g_{\sigma B'}}{m_\sigma^2}\frac{(2J_{B'}+1)}{(2\pi)^3}M_{B'}^*\int\frac{\theta(k_{F_{B'}}-|\vec{k}|)\,d^3k}{\sqrt{\vec{k}^2+M_{B'}^{*2}}}\end{aligned}$$

Hyperonic QMC

- $B \in \{p, n, \Lambda, \Sigma^-, \Sigma^0, \Sigma^+, \Xi^-, \Xi^0\} = \{N, Y\}$
- $\ell \in \{e^-, \mu^-\}$
- $m \in \{\sigma, \omega, \rho\}$

Couplings:

$$g_{\omega B} = \frac{(3 - S_B)}{3}\, g_{\omega N}$$

$$g_{\omega N} = \frac{3}{2} g_{\omega\Lambda} = \frac{3}{2} g_{\omega\Sigma} = 3 g_{\omega\Xi}$$

Hyperonic QMC

- $B \in \{p, n, \Lambda, \Sigma^-, \Sigma^0, \Sigma^+, \Xi^-, \Xi^0\} = \{N, Y\}$
- $\ell \in \{e^-, \mu^-\}$
- $m \in \{\sigma, \omega, \rho\}$

Couplings:

$$g_{\omega B} = \frac{(3 - S_B)}{3}\, g_{\omega N}$$

$$g_{\omega N} = \frac{3}{2} g_{\omega\Lambda} = \frac{3}{2} g_{\omega\Sigma} = 3 g_{\omega\Xi}$$

Hyperonic QMC

- $B \in \{p, n, \Lambda, \Sigma^-, \Sigma^0, \Sigma^+, \Xi^-, \Xi^0\} = \{N, Y\}$
- $\ell \in \{e^-, \mu^-\}$
- $m \in \{\sigma, \omega, \rho\}$

Couplings:

$$g_{\omega B} = \frac{(3 - S_B)}{3}\, g_{\omega N}$$

$$g_{\omega N} = \frac{3}{2} g_{\omega \Lambda} = \frac{3}{2} g_{\omega \Sigma} = 3 g_{\omega \Xi}$$

Hyperonic QMC

- $B \in \{p, n, \Lambda, \Sigma^-, \Sigma^0, \Sigma^+, \Xi^-, \Xi^0\} = \{N, Y\}$
- $\ell \in \{e^-, \mu^-\}$
- $m \in \{\sigma, \omega, \rho\}$

Couplings:

$$g_{\omega B} = \frac{(3 - S_B)}{3}\ g_{\omega N}$$

$$g_{\omega N} = \frac{3}{2} g_{\omega \Lambda} = \frac{3}{2} g_{\omega \Sigma} = 3 g_{\omega \Xi}$$

Hyperonic QMC

- $B \in \{p, n, \Lambda, \Sigma^-, \Sigma^0, \Sigma^+, \Xi^-, \Xi^0\} = \{N, Y\}$
- $\ell \in \{e^-, \mu^-\}$
- $m \in \{\sigma, \omega, \rho\}$

Couplings:

$$g_{\omega B} = \frac{(3 - S_B)}{3}\, g_{\omega N}$$

$$g_{\omega N} = \frac{3}{2} g_{\omega \Lambda} = \frac{3}{2} g_{\omega \Sigma} = 3 g_{\omega \Xi}$$

Hyperonic QMC

- $B \in \{p, n, \Lambda, \Sigma^-, \Sigma^0, \Sigma^+, \Xi^-, \Xi^0\} = \{N, Y\}$
- $\ell \in \{e^-, \mu^-\}$
- $m \in \{\sigma, \omega, \rho\}$

Couplings:

$$g_{\omega B} = \frac{(3 - S_B)}{3} \; g_{\omega N}$$

$$g_{\omega N} = \frac{3}{2} g_{\omega\Lambda} = \frac{3}{2} g_{\omega\Sigma} = 3 g_{\omega\Xi}$$

Hyperonic QMC

Saturation

$$\left.\begin{aligned} (E/A)_{\rho_0} &= -15.86 \text{ MeV}, \\ (\rho_{\text{total}})_{\rho_0} &= 0.16 \text{ fm}^{-3} \end{aligned}\right\} \quad -- \quad g_{\sigma N},\ g_{\omega N}$$

$$(a_{sym})_{\rho_0} = 32.5 \text{ Mev} \quad -- \quad g_{\rho N}$$

Hyperonic QMC

Saturation

$$\left.\begin{aligned}(E/A)_{\rho_0} &= -15.86 \text{ MeV},\\ (\rho_{\text{total}})_{\rho_0} &= 0.16 \text{ fm}^{-3}\end{aligned}\right\} \quad -- \quad g_{\sigma N},\ g_{\omega N}$$

$$(a_{sym})_{\rho_0} = 32.5 \text{ Mev} \quad -- \quad g_{\rho N}$$

Hyperonic QMC

Saturation

$$\left.\begin{aligned}(E/A)_{\rho_0} &= -15.86\ \text{MeV},\\ (\rho_{\text{total}})_{\rho_0} &= 0.16\ \text{fm}^{-3}\end{aligned}\right\} \quad -- \quad g_{\sigma N},\ g_{\omega N}$$

$$(a_{sym})_{\rho_0} = 32.5\ \text{Mev} \quad -- \quad g_{\rho N}$$

Effective masses from Ref. [4][a] (previously from Ref. [5][b]) derived from the bag model.

[a] Guichon, Thomas, Tsushima: doi:10.1016/j.nuclphysa.2008.10.001

[b] Rikovska-Stone, Guichon, Matevosyan, Thomas: doi:10.1016/j.nuclphysa.2007.05.011

Hyperonic QMC

Equation of State (EOS) is calculated assuming that

Chemical Equilibrium

$$\mu_i = B_i\,\mu_n - Q_i\,\mu_e = \sqrt{k_{F_i}^2 + (M_i + \Sigma_i^s)^2} + \Sigma_i^0$$

Hyperonic QMC

Equation of State (EOS) is calculated assuming that

Chemical Equilibrium

$$\mu_i = B_i \, \mu_n - Q_i \, \mu_e = \sqrt{k_{F_i}^2 + (M_i + \Sigma_i^s)^2} + \Sigma_i^0$$

Hyperonic QMC

Equation of State (EOS) is calculated assuming that

Chemical Equilibrium

$$\mu_i = B_i \, \mu_n - Q_i \, \mu_e = \sqrt{k_{F_i}^2 + (M_i + \Sigma_i^s)^2} + \Sigma_i^0$$

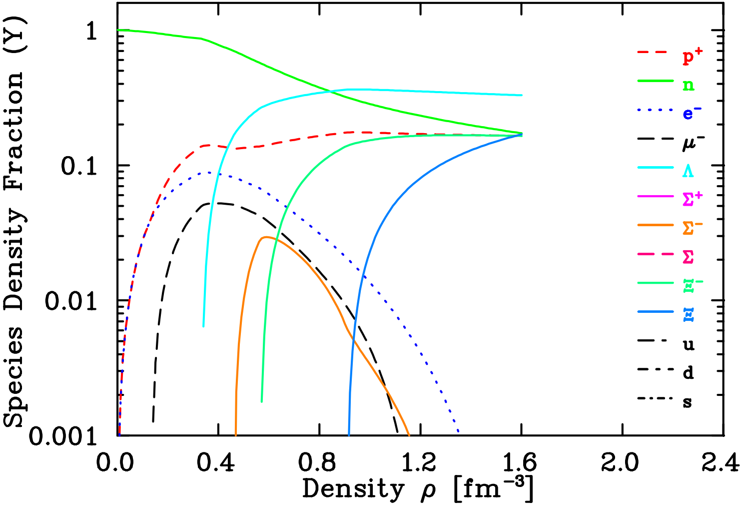
Hyperonic QMC

Equation of State (EOS) is calculated assuming that

Chemical Equilibrium

$$\mu_i = B_i\,\mu_n - Q_i\,\mu_e = \sqrt{k_{F_i}^2 + (M_i + \Sigma_i^s)^2} + \Sigma_i^0$$

Hyperonic QMC



Tolman-Oppenheimer-Volkoff

Equations describe a static, spherically symmetric, non-rotating star, stable against gravitational collapse;

TOV

$$\frac{dP}{dr} = -\frac{G\left(P/c^2+\mathcal{E}\right)\left(M(r)+4r^3\pi P/c^2\right)}{r(r-2GM(r)/c^2)}$$

$$M(R) = \int_0^R 4\pi r^2 \mathcal{E}(r)\, dr$$

Tolman-Oppenheimer-Volkoff

Equations describe a static, spherically symmetric, non-rotating star, stable against gravitational collapse;

TOV

$$\begin{aligned} \frac{dP}{dr} &= -\frac{G\left(P/c^2+\mathcal{E}\right)\left(M(r)+4r^3\pi P/c^2\right)}{r(r-2GM(r)/c^2)} \\ M(R) &= \int_0^R 4\pi r^2 \mathcal{E}(r)\, dr \end{aligned}$$

Tolman-Oppenheimer-Volkoff

Equations describe a static, spherically symmetric, non-rotating star, stable against gravitational collapse;

TOV

$$\frac{dP}{dr} = -\frac{G\left(P/c^2 + \mathcal{E}\right)\left(M(r) + 4r^3\pi P/c^2\right)}{r(r - 2GM(r)/c^2)}$$

$$M(R) = \int_0^R 4\pi r^2 \mathcal{E}(r)\, dr$$

Tolman-Oppenheimer-Volkoff

Equations describe a static, spherically symmetric, non-rotating star, stable against gravitational collapse;

TOV

$$\frac{dP}{dr} = -\frac{G\left(P/c^2 + \mathcal{E}\right)\left(M(r) + 4r^3\pi P/c^2\right)}{r(r - 2GM(r)/c^2)}$$

$$M(R) = \int_0^R 4\pi r^2 \mathcal{E}(r)\, dr$$

There are issues with experimental constraints

Determining M experimentally is easy*...

There are issues with experimental constraints

Determining M experimentally is easy*... BUT!

There are issues with experimental constraints

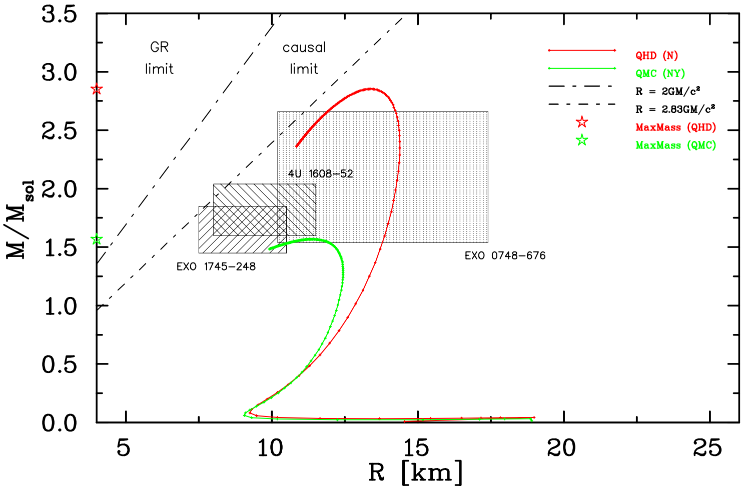
Determining M experimentally is easy*... BUT!

There is very little experimental data for R.

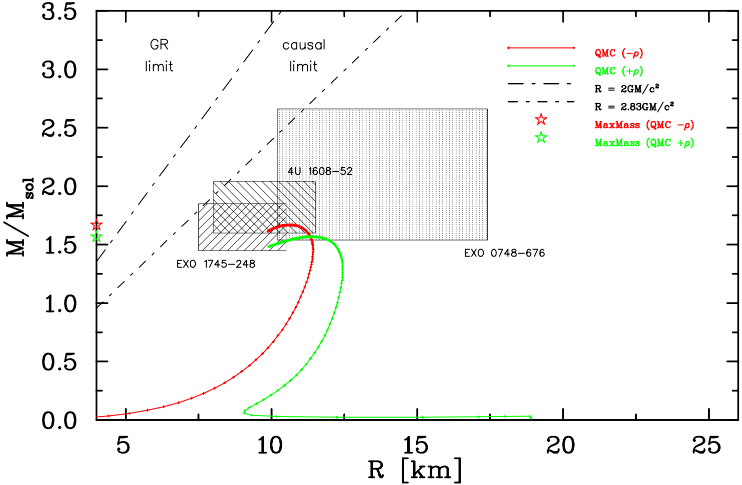
There are issues with experimental constraints

Determining M experimentally is easy*... BUT!
There is very little experimental data for R.

Hyperonic QMC
TOV solutions



Hyperonic QMC
TOV solutions



Quark Models
A Brief Overview

MIT Bag Model

- 3 quarks in a '*bag*',
- Separated from the QCD vacuum by an energy-density B,
- Constant, current-quark masses

Nambu-**J**ona–**L**asinio (**NJL**) Model

- Simple inclusion of DχSB,
- Still a simple model, but more sophisticated,
- Constituent-quark masses at low density, current-quark masses at high density.

Quark Models
A Brief Overview

MIT Bag Model

- 3 quarks in a '*bag*',
- Separated from the QCD vacuum by an energy-density B,
- Constant, current-quark masses

Nambu-**J**ona–**L**asinio (**NJL**) Model

- Simple inclusion of DχSB,
- Still a simple model, but more sophisticated,
- Constituent-quark masses at low density, current-quark masses at high density.

Quark Models
A Brief Overview

MIT Bag Model

- 3 quarks in a '*bag*',
- Separated from the QCD vacuum by an energy-density B,
- Constant, current-quark masses

Nambu-**J**ona–**L**asinio (**NJL**) Model

- Simple inclusion of DχSB,
- Still a simple model, but more sophisticated,
- Constituent-quark masses at low density, current-quark masses at high density.

Quark Models
A Brief Overview

MIT Bag Model

- 3 quarks in a '*bag*',
- Separated from the QCD vacuum by an energy-density B,
- Constant, current-quark masses

Nambu-**J**ona–**L**asinio (**NJL**) Model

- Simple inclusion of DχSB,
- Still a simple model, but more sophisticated,
- Constituent-quark masses at low density, current-quark masses at high density.

Quark Models
A Brief Overview

MIT Bag Model

MIT:

$$m_u = 5 \text{ MeV}, \; m_d = 7 \text{ MeV}, \; m_s = 95 \text{ MeV}$$

Nambu-**J**ona–**L**asinio (**NJL**) Model

- Simple inclusion of DχSB,
- Still a simple model, but more sophisticated,
- Constituent-quark masses at low density, current-quark masses at high density.

Quark Models
A Brief Overview

MIT Bag Model

MIT:

$$m_u = 5\ \text{MeV},\ m_d = 7\ \text{MeV},\ m_s = 95\ \text{MeV}$$

Nambu-**J**ona–**L**asinio (**NJL**) Model

- Simple inclusion of DχSB,
- Still a simple model, but more sophisticated,
- Constituent-quark masses at low density, current-quark masses at high density.

Quark Models
A Brief Overview

MIT Bag Model

MIT:

$$m_u = 5 \text{ MeV}, \; m_d = 7 \text{ MeV}, \; m_s = 95 \text{ MeV}$$

Nambu-**J**ona–**L**asinio (**NJL**) Model

- Simple inclusion of DχSB,
- Still a simple model, but more sophisticated,
- Constituent-quark masses at low density, current-quark masses at high density.

Quark Models
A Brief Overview

MIT Bag Model

MIT:

$$m_u = 5 \text{ MeV},\ m_d = 7 \text{ MeV},\ m_s = 95 \text{ MeV}$$

Nambu-**J**ona–**L**asinio (**NJL**) Model

- Simple inclusion of DχSB,
- Still a simple model, but more sophisticated,
- Constituent-quark masses at low density, current-quark masses at high density.

Quark Models
A Brief Overview

MIT Bag Model

MIT:

$$m_u = 5 \text{ MeV},\ m_d = 7 \text{ MeV},\ m_s = 95 \text{ MeV}$$

Nambu-**J**ona–**L**asinio (**NJL**) Model

- Simple inclusion of DχSB,
- Still a simple model, but more sophisticated,
- Constituent-quark masses at low density, current-quark masses at high density.

Quark Models
A Brief Overview

MIT Bag Model

MIT:

$$m_u = 5 \text{ MeV},\ m_d = 7 \text{ MeV},\ m_s = 95 \text{ MeV}$$

Nambu-**J**ona–**L**asinio (**NJL**) Model

NJL:

$$\begin{aligned} m_q^* &= m_q + \Sigma_q^s = m_q - 2G\langle\bar{\psi}_q\psi_q\rangle \\ &= m_q + \frac{8G\mathcal{N}_c}{(2\pi)^3}\int \frac{\theta(k_F - |\vec{k}|)\theta(\Lambda - k_F)m_q^*}{\sqrt{\vec{k}^2 + m_q^{*2}}} \end{aligned}$$

Quark Models
A Brief Overview

MIT Bag Model

MIT:

$$m_u = 5 \text{ MeV}, \;\; m_d = 7 \text{ MeV}, \;\; m_s = 95 \text{ MeV}$$

Nambu-**J**ona–**L**asinio (**NJL**) Model

NJL:

$$\begin{aligned} m_q^* &= m_q + \Sigma_q^s = m_q - 2G\langle\bar{\psi}_q\psi_q\rangle \\ &= m_q + \frac{8G\mathcal{N}_c}{(2\pi)^3}\int \frac{\theta(k_F - |\vec{k}|)\theta(\Lambda - k_F)m_q^*}{\sqrt{\vec{k}^2 + m_q^{*2}}} \end{aligned}$$

Quark Models
A Brief Overview

MIT Bag Model

MIT:

$$m_u = 5 \text{ MeV},\ m_d = 7 \text{ MeV},\ m_s = 95 \text{ MeV}$$

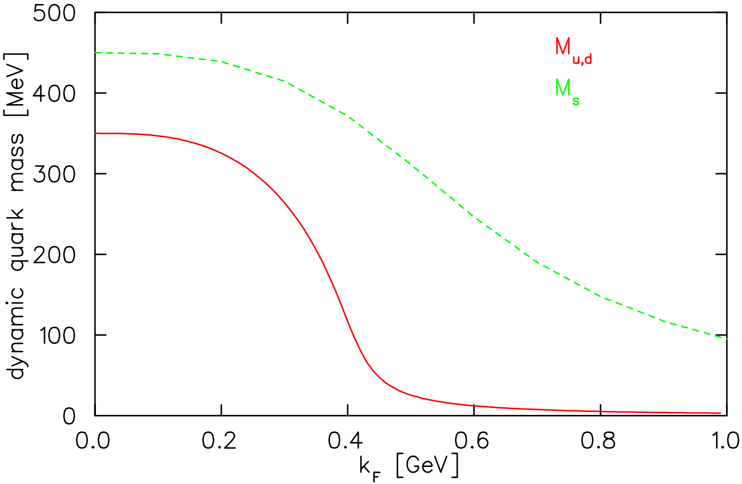
Nambu-**J**ona–**L**asinio (**NJL**) Model

NJL:

$$k_F = 0 \ :\ m_u = 350 \text{ MeV},\ m_d = 350 \text{ MeV},\ m_s = 450 \text{ MeV}$$
$$k_F = \Lambda \ :\ m_u = 5 \text{ MeV},\ m_d = 7 \text{ MeV},\ m_s = 95 \text{ MeV}$$

Quark Models

NJL Effective Masses



Phase Transitions

The Gibbs Conditions for a phase transition are;

Gibbs Conditions

- $T_H = T_Q$ – Thermal Equilibrium
- $(\mu_i)_H = (\mu_i)_Q$ – Chemical Equilibrium
- $P_H = P_Q$ – Mechanical Equilibrium

Phase Transitions

The Gibbs Conditions for a phase transition are;

Gibbs Conditions

- $T_H = T_Q$ – Thermal Equilibrium
- $(\mu_i)_H = (\mu_i)_Q$ – Chemical Equilibrium
- $P_H = P_Q$ – Mechanical Equilibrium

Phase Transitions

The Gibbs Conditions for a phase transition are;

Gibbs Conditions

- $T_H = T_Q$ – Thermal Equilibrium
- $(\mu_i)_H = (\mu_i)_Q$ – Chemical Equilibrium
- $P_H = P_Q$ – Mechanical Equilibrium

Phase Transitions

The Gibbs Conditions for a phase transition are;

Gibbs Conditions

- $T_H = T_Q$ – Thermal Equilibrium
- $(\mu_i)_H = (\mu_i)_Q$ – Chemical Equilibrium
- $P_H = P_Q$ – Mechanical Equilibrium

Phase Transitions

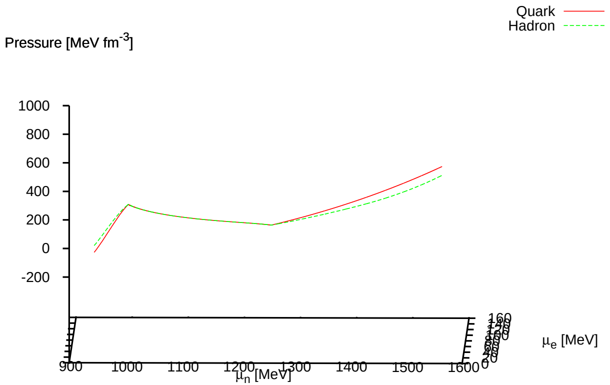
The Gibbs Conditions for a phase transition are;

Gibbs Conditions

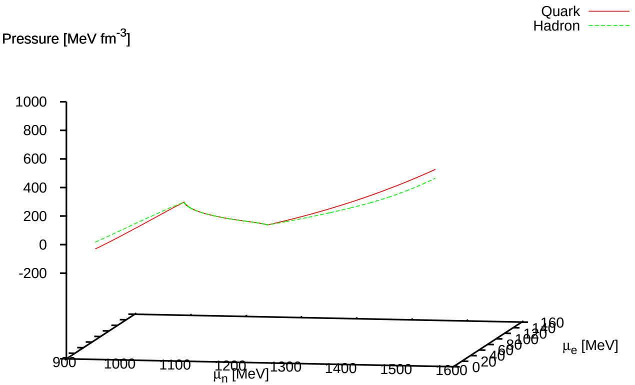
$\swarrow$ $T = 0$

- $T_H = T_Q$ – Thermal Equilibrium
- $(\mu_i)_H = (\mu_i)_Q$ – Chemical Equilibrium
- $P_H = P_Q$ – Mechanical Equilibrium

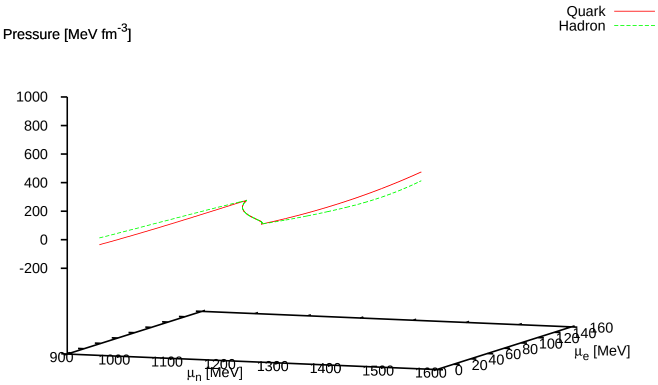
Mixed Phase


Quark
Hadron
Pressure [MeV fm^-3]
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μn [MeV]
160
0
μe [MeV]

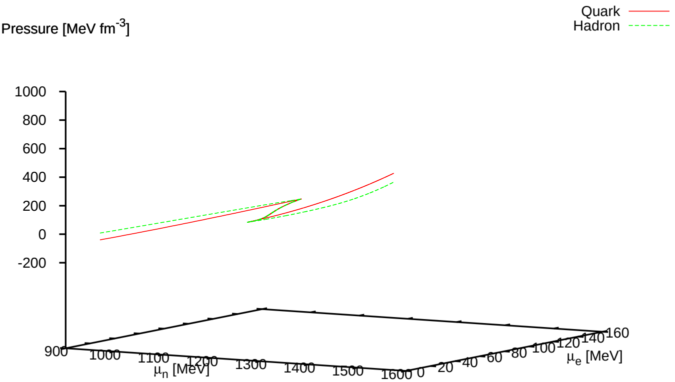
Mixed Phase


Quark
Hadron
Pressure [MeV fm-3]
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μn [MeV]
0
20
40
60
80
100
120
140
160
μe [MeV]

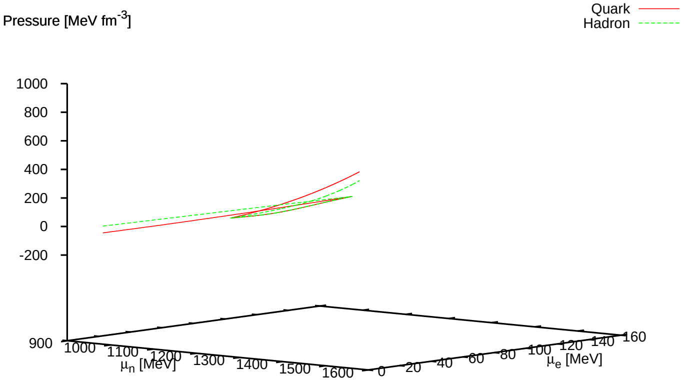
Mixed Phase


Quark
Hadron
Pressure [MeV fm^-3]
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μn [MeV]
0
20
40
60
80
100
120
140
160
μe [MeV]

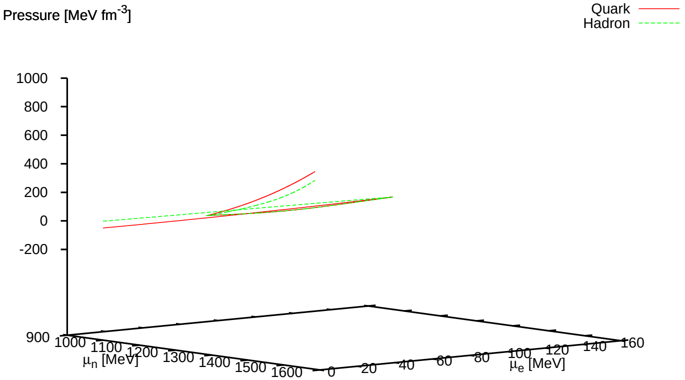
Mixed Phase


Pressure [MeV fm^{-3}]
Quark
Hadron
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μ_n [MeV]
0
20
40
60
80
100
120
140
160
μ_e [MeV]

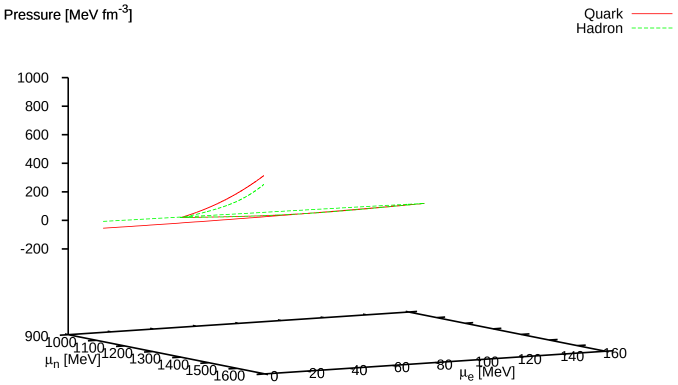
Mixed Phase


Pressure [MeV fm^{-3}]
Quark
Hadron
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μ_n [MeV]
0
20
40
60
80
100
120
140
160
μ_e [MeV]

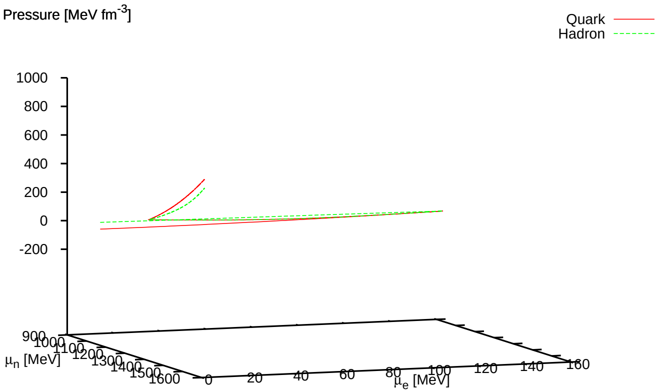
Mixed Phase


Pressure [MeV fm^{-3}]
Quark
Hadron
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μ_n [MeV]
0
20
40
60
80
100
120
140
160
μ_e [MeV]

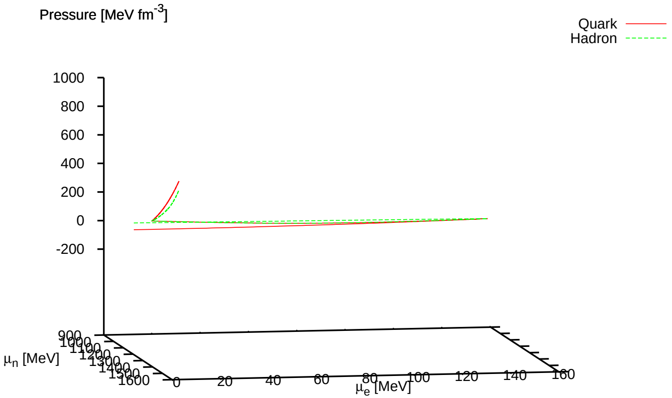
Mixed Phase


Pressure [MeV fm-3]
Quark
Hadron
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μn [MeV]
0
20
40
60
80
100
120
140
160
μe [MeV]

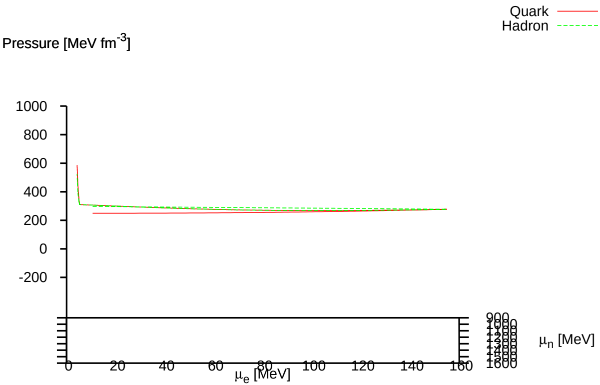
Mixed Phase


Pressure [MeV fm-3]
Quark
Hadron
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μn [MeV]
0
20
40
60
80
100
120
140
160
μe [MeV]

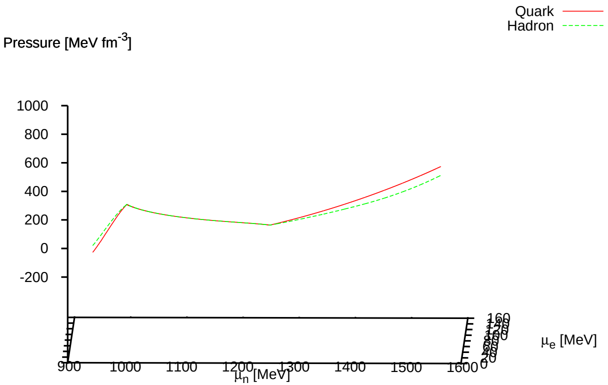
Mixed Phase


Pressure [MeV fm^{-3}]
Quark
Hadron
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μ_n [MeV]
0
20
40
60
80
100
120
140
160
μ_e [MeV]

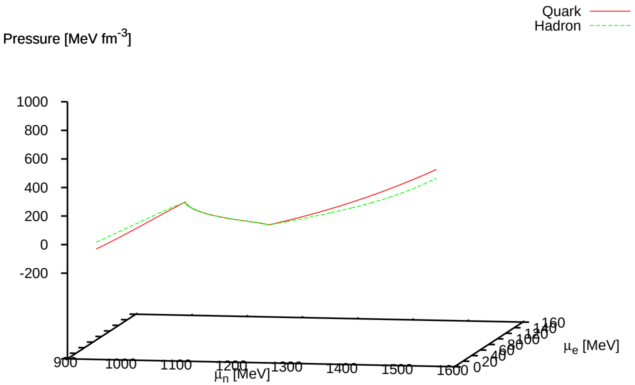
Mixed Phase


Quark
Hadron
Pressure [MeV fm^{-3}]
1000
800
600
400
200
0
-200
0
20
40
60
80
100
120
140
160
μ_e [MeV]
900
1600
μ_n [MeV]

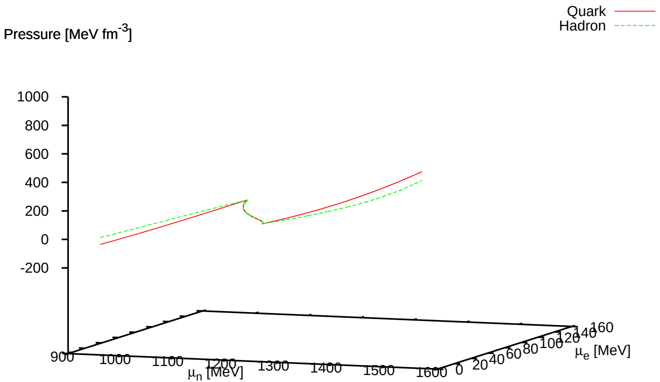
Mixed Phase


Quark
Hadron
Pressure [MeV fm^-3]
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μn [MeV]
160
0
μe [MeV]

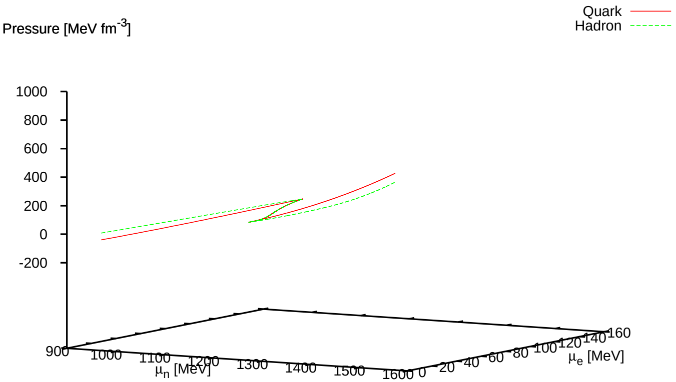
Mixed Phase


Quark
Hadron
Pressure [MeV fm^{-3}]
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μ_n [MeV]
μ_e [MeV]
160

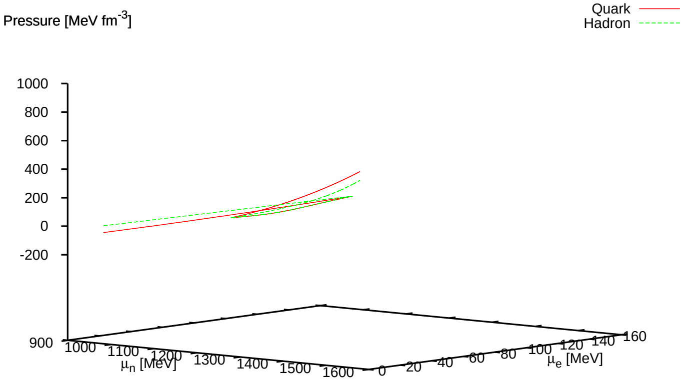
Mixed Phase


Quark
Hadron
Pressure [MeV fm^-3]
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μn [MeV]
0
20
40
60
80
100
120
140
160
μe [MeV]

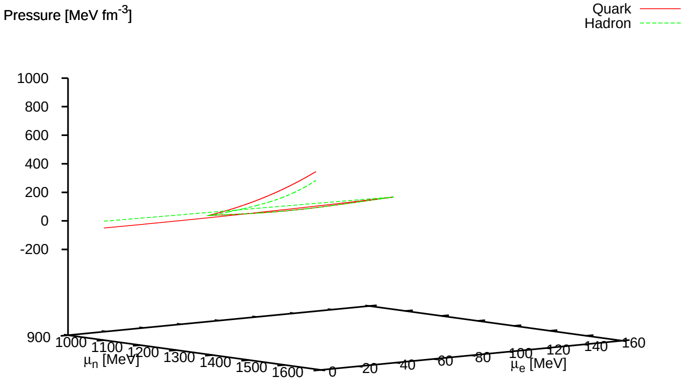
Mixed Phase


Pressure [MeV fm-3]
Quark
Hadron
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μn [MeV]
0
20
40
60
80
100
120
140
160
μe [MeV]

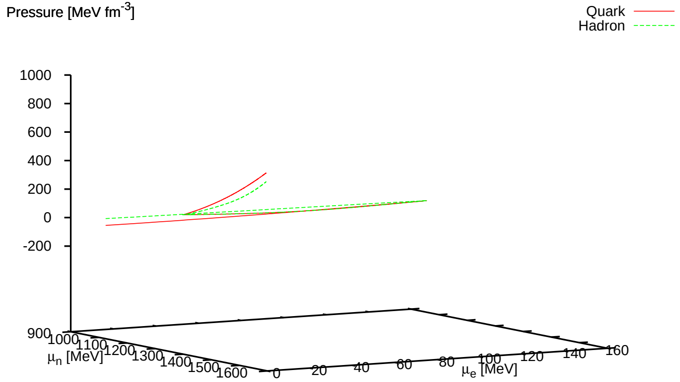
Mixed Phase


Pressure [MeV fm^-3]
Quark
Hadron
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μn [MeV]
0
20
40
60
80
100
120
140
160
μe [MeV]

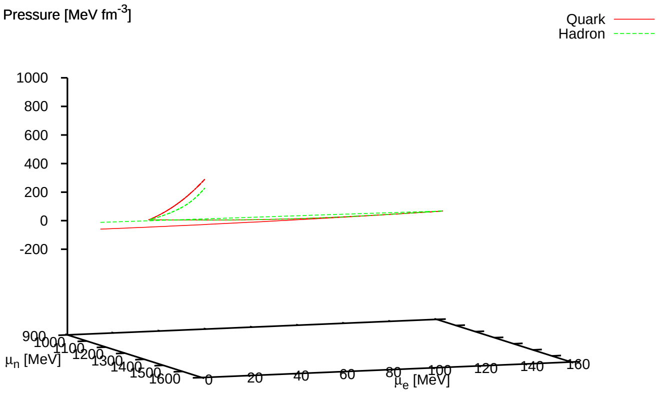
Mixed Phase


Pressure [MeV fm^{-3}]
Quark
Hadron
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μ_n [MeV]
0
20
40
60
80
100
120
140
160
μ_e [MeV]

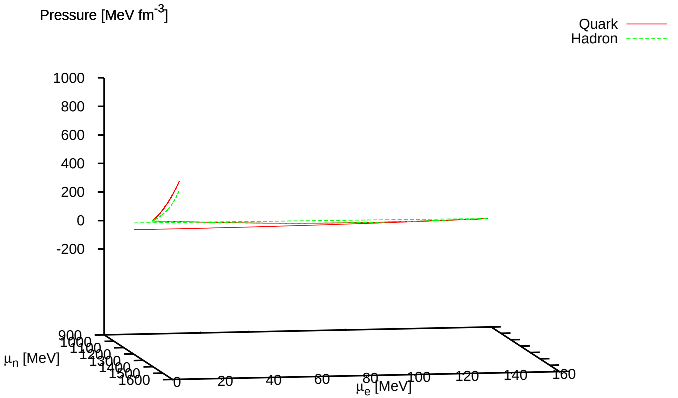
Mixed Phase


Pressure [MeV fm-3]
Quark
Hadron
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μn [MeV]
0
20
40
60
80
100
120
140
160
μe [MeV]

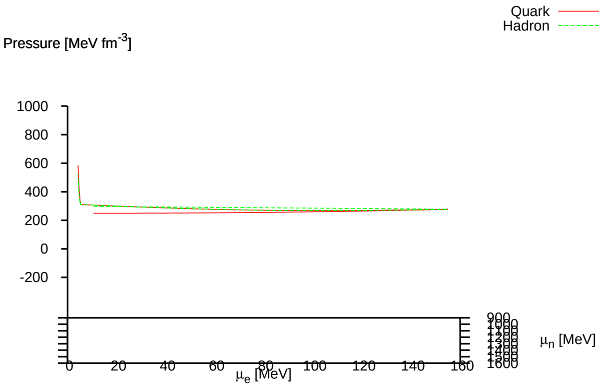
Mixed Phase


Pressure [MeV fm^{-3}]
Quark
Hadron
1000
800
600
400
200
0
-200
900
1000
1100
1200
1300
1400
1500
1600
μ_n [MeV]
0
20
40
60
80
100
120
140
160
μ_e [MeV]

Mixed Phase

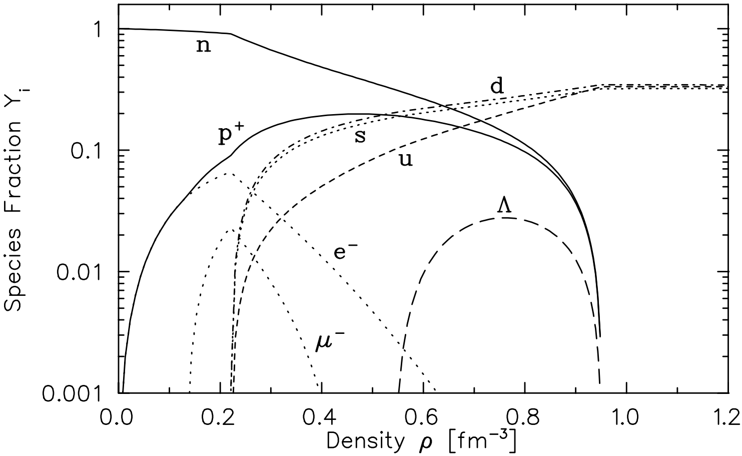

Pressure [MeV fm^-3]
Quark
Hadron
1000
800
600
400
200
0
-200
μn [MeV]
900
1000
1100
1200
1300
1400
1500
1600
0
20
40
60
80
100
120
140
160
μe [MeV]

Mixed Phase

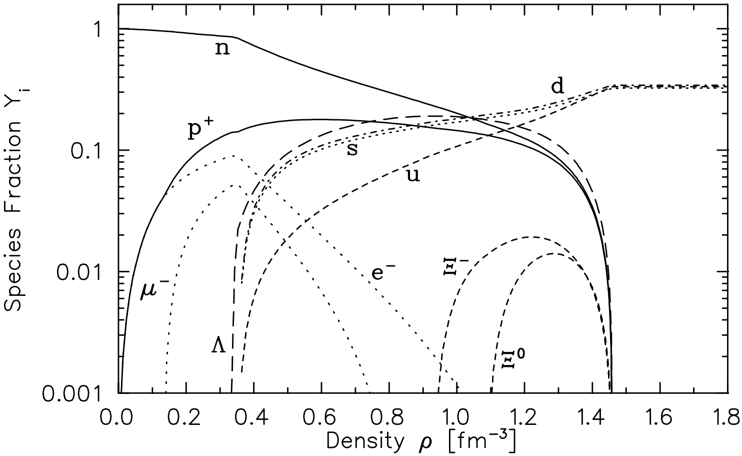

Quark
Hadron
Pressure [MeV fm^-3]
1000
800
600
400
200
0
-200
0
20
40
60
80
100
120
140
160
μe [MeV]
900
1600
μn [MeV]

Hyperonic QMC

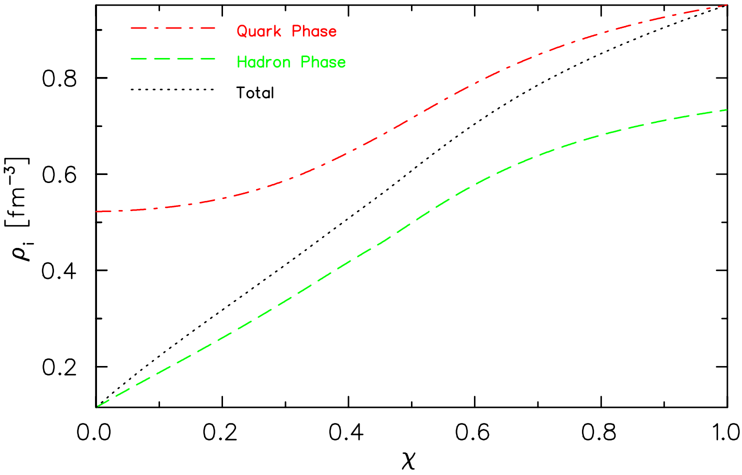
Phase Transition



Hyperonic QMC
Phase Transition



Hyperonic QMC
Phase Transition



Phase Transitions

Chemical Potentials

Quark Chemical Potentials related to independent chemical potentials;

Chemical Equilibrium - baryons

$$\mu_i = B_i\,\mu_n - Q_i\,\mu_e = \sqrt{k_{F_i}^2 + (M_i + \Sigma_i^s)^2} + \Sigma_i^0$$

Phase Transitions

Chemical Potentials

Quark Chemical Potentials related to independent chemical potentials;

Chemical Equilibrium - baryons

$$\mu_i = B_i \, \mu_n - Q_i \, \mu_e = \sqrt{k_{F_i}^2 + (M_i + \Sigma_i^s)^2} + \Sigma_i^0$$

Phase Transitions
Chemical Potentials

Quark Chemical Potentials related to independent chemical potentials;

Chemical Equilibrium - baryons

$$\mu_i = B_i\,\mu_n - Q_i\,\mu_e = \sqrt{k_{F_i}^2 + (M_i + \Sigma_i^s)^2} + \Sigma_i^0$$

Phase Transitions
Chemical Potentials

Quark Chemical Potentials related to independent chemical potentials;

Chemical Equilibrium - baryons

$$\mu_i = B_i\,\mu_n - Q_i\,\mu_e = \sqrt{k_{F_i}^2 + (M_i + \Sigma_i^s)^2} + \Sigma_i^0$$

Phase Transitions
Chemical Potentials

Quark Chemical Potentials related to independent chemical potentials;

Chemical Equilibrium - quarks

$$\mu_i = B_i \, \mu_n - Q_i \, \mu_e = \sqrt{k_{F_i}^2 + M_i^2}$$

Phase Transitions
Chemical Potentials

Quark Chemical Potentials related to independent chemical potentials;

Chemical Equilibrium - quarks

$$\mu_i = B_i\, \mu_n - Q_i\, \mu_e = \sqrt{k_{F_i}^2 + M_i^2}$$

Phase Transitions
Chemical Potentials

Quark Chemical Potentials related to independent chemical potentials;

Chemical Equilibrium - quarks

$$\mu_i = B_i\,\mu_n - Q_i\,\mu_e = \sqrt{k_{F_i}^2 + M_i^2}$$

Phase Transitions
Chemical Potentials

Quark Chemical Potentials related to independent chemical potentials;

Chemical Equilibrium - quarks

$$\mu_i = B_i\,\mu_n - Q_i\,\mu_e = \sqrt{k_{F_i}^2 + M_i^2}$$

Phase Transitions

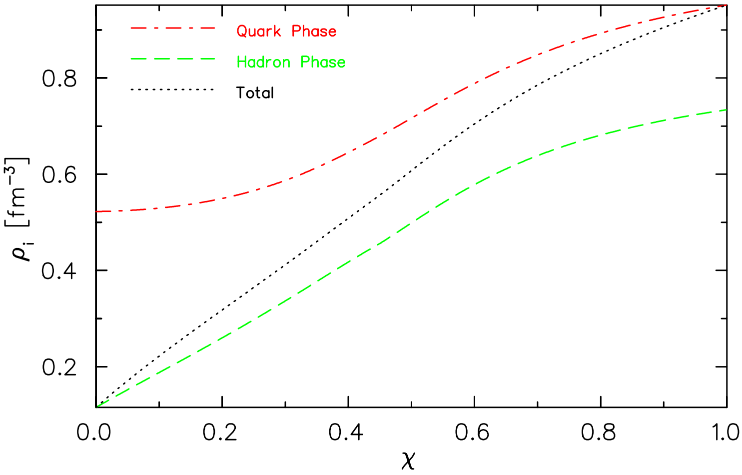
Chemical Potentials

Quark Chemical Potentials related to independent chemical potentials;

Chemical Equilibrium - quarks

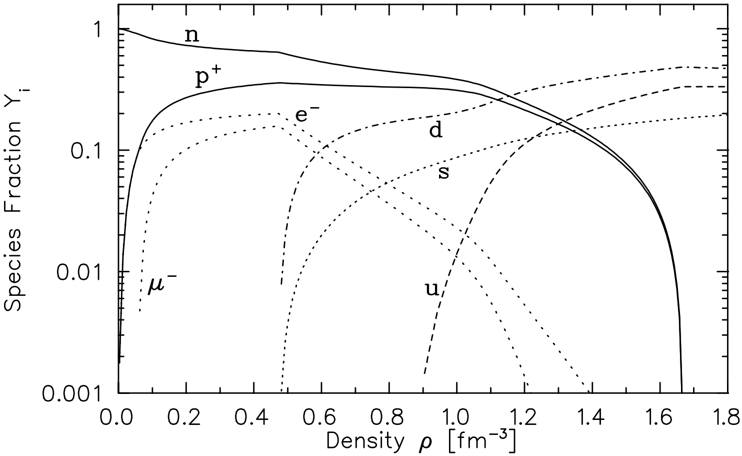
$$\mu_i = \frac{1}{3}\,\mu_n - Q_i\,\mu_e$$

Hyperonic QMC
Phase Transition



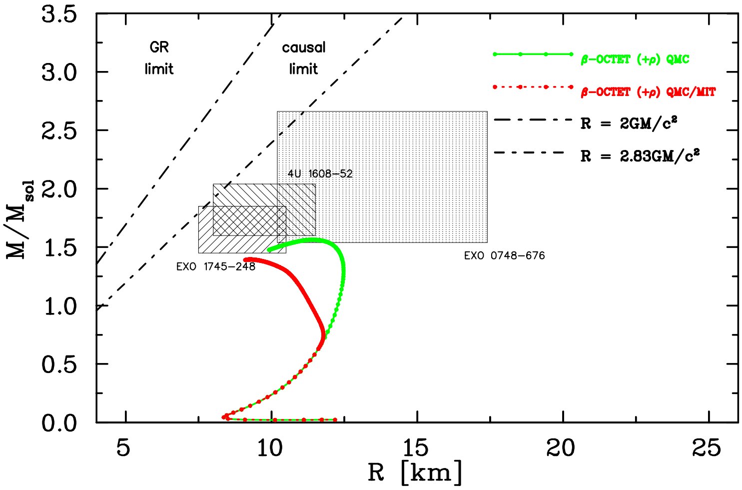
Hyperonic QMC

Phase Transition



Mixed-Phase Hyperonic QMC

TOV solutions



Summary

- The inclusion of DχSB prevents a phase transition to quark matter,
- The predictions are very sensitive to changes in model parameters,
- Good agreement with experimental data is possible,
- The most likely degrees of freedom at high-density are still unknown.

Summary

- The inclusion of DχSB prevents a phase transition to quark matter,
- The predictions are very sensitive to changes in model parameters,
- Good agreement with experimental data is possible,
- The most likely degrees of freedom at high-density are still unknown.

Summary

- The inclusion of DχSB prevents a phase transition to quark matter, (dependent on HM/QM model)
- The predictions are very sensitive to changes in model parameters,
- Good agreement with experimental data is possible,
- The most likely degrees of freedom at high-density are still unknown.

Summary

- The inclusion of DχSB prevents a phase transition to quark matter, (dependent on HM/QM model)
- The predictions are very sensitive to changes in model parameters,
- Good agreement with experimental data is possible,
- The most likely degrees of freedom at high-density are still unknown.

Summary

- The inclusion of DχSB prevents a phase transition to quark matter, (dependent on HM/QM model)
- The predictions are very sensitive to changes in model parameters,
- Good agreement with experimental data is possible,
- The most likely degrees of freedom at high-density are still unknown.

Summary

- The inclusion of DχSB prevents a phase transition to quark matter, (dependent on HM/QM model)
- The predictions are very sensitive to changes in model parameters,
- Good agreement with experimental data is possible, (*but this occurs for **most** models!*)
- The most likely degrees of freedom at high-density are still unknown.

Summary

- The inclusion of DχSB prevents a phase transition to quark matter, (dependent on HM/QM model)
- The predictions are very sensitive to changes in model parameters,
- Good agreement with experimental data is possible, (*but this occurs for **most** models!*)
- The most likely degrees of freedom at high-density are still unknown.

Summary

- The inclusion of DχSB prevents a phase transition to quark matter, (dependent on HM/QM model)
- The predictions are very sensitive to changes in model parameters,
- Good agreement with experimental data is possible, (*but this occurs for **most** models!*)
- The most likely degrees of freedom at high-density are still unknown.

- Outlook:
  - Inclusion of Fock terms
  - Inclusion of π contributions (Fock)
  - Additional potential terms
  - Effects of Fock terms in Finite Nuclei calculations

Summary

- The inclusion of DχSB prevents a phase transition to quark matter, (dependent on HM/QM model)
- The predictions are very sensitive to changes in model parameters,
- Good agreement with experimental data is possible, (*but this occurs for **most** models!*)
- The most likely degrees of freedom at high-density are still unknown.

- Outlook:
  - Inclusion of Fock terms
  - Inclusion of π contributions (Fock)
  - Additional potential terms
  - Effects of Fock terms in Finite Nuclei calculations

Summary

- The inclusion of DχSB prevents a phase transition to quark matter, (dependent on HM/QM model)
- The predictions are very sensitive to changes in model parameters,
- Good agreement with experimental data is possible, (*but this occurs for* ***most*** *models!*)
- The most likely degrees of freedom at high-density are still unknown.

- Outlook:
  - Inclusion of Fock terms
  - Inclusion of π contributions (Fock)
  - Additional potential terms
  - Effects of Fock terms in Finite Nuclei calculations

Summary

- The inclusion of DχSB prevents a phase transition to quark matter, (dependent on HM/QM model)
- The predictions are very sensitive to changes in model parameters,
- Good agreement with experimental data is possible, (*but this occurs for **most** models!*)
- The most likely degrees of freedom at high-density are still unknown.

- Outlook:
  - Inclusion of Fock terms
  - Inclusion of π contributions (Fock)
  - Additional potential terms
  - Effects of Fock terms in Finite Nuclei calculations

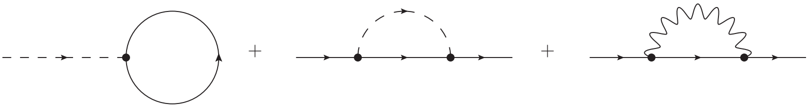
Summary

- The inclusion of DχSB prevents a phase transition to quark matter, (dependent on HM/QM model)
- The predictions are very sensitive to changes in model parameters,
- Good agreement with experimental data is possible, (*but this occurs for **most** models!*)
- The most likely degrees of freedom at high-density are still unknown.

- Outlook:
  - Inclusion of Fock terms
  - Inclusion of π contributions (Fock)
  - Additional potential terms
  - Effects of Fock terms in Finite Nuclei calculations

Hadronic Models
A Brief Overview: Hartree–Fock

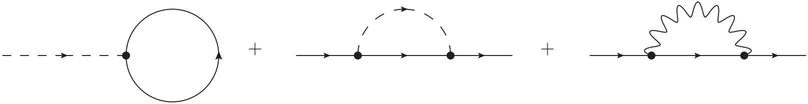
At Hartree–Fock level, the scalar self-energy also includes an exchange term, and becomes momentum-dependent:



Hadronic Models

A Brief Overview: Hartree–Fock

At Hartree–Fock level, the scalar self-energy also includes an exchange term, and becomes momentum-dependent:

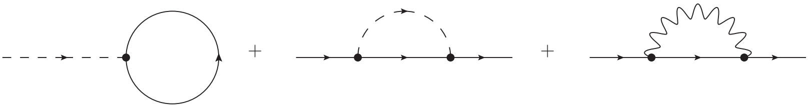


Hartree–Fock $\Sigma^s_B(k)$ (QHD)

$$\begin{aligned}\Sigma^s_B(k) &= -g_{\sigma B}\langle\sigma\rangle \\ &+ \frac{1}{4\pi^2 k}\int_0^{k_{F_{B'}}} \frac{q\, M^*_B(q)}{E^*_B(q)} \\ &\quad \times \left[\frac{1}{4}g^2_{\sigma B'}\Theta_\sigma(k,q) - g^2_{\omega B'}\Theta_\omega(k,q)\right]\, dq\end{aligned}$$

Hadronic Models
A Brief Overview: Hartree–Fock

At Hartree–Fock level, the scalar self-energy also includes an exchange term, and becomes momentum-dependent:



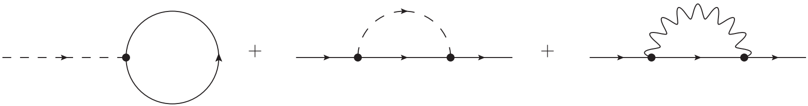
Hartree–Fock $\Sigma^s_B(k)$ (QHD)

$$\begin{aligned}\Sigma^s_B(k) &= -g_{\sigma B}\langle\sigma\rangle \\ &+ \frac{1}{4\pi^2 k}\int_0^{k_{F_{B'}}} \frac{q\ M^*_B(q)}{E^*_B(q)} \\ &\quad\times\left[\frac{1}{4}g^2_{\sigma B'}\Theta_\sigma(k,q) - g^2_{\omega B'}\Theta_\omega(k,q)\right]\ dq\end{aligned}$$

Hadronic Models

A Brief Overview: Hartree–Fock

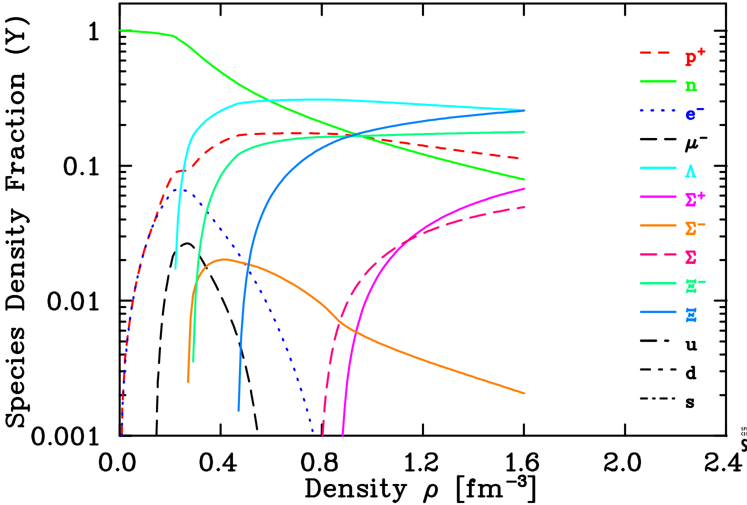
At Hartree–Fock level, the scalar self-energy also includes an exchange term, and becomes momentum-dependent:



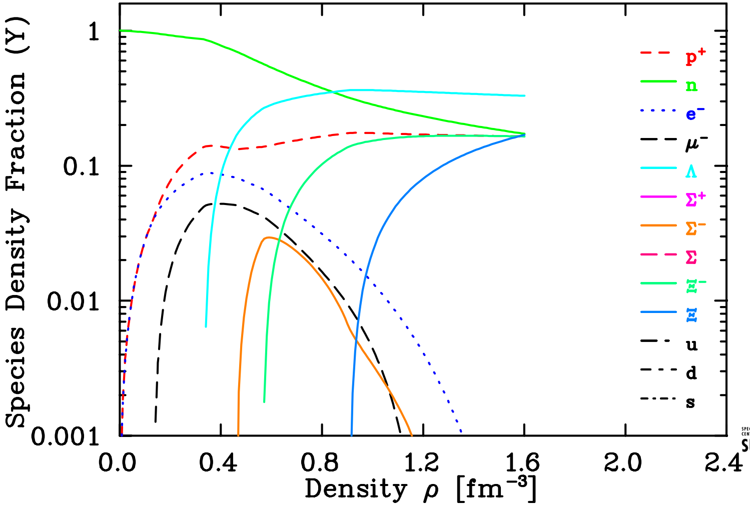
Hartree–Fock $\Sigma^s_B(k)$ (QHD)

$$\Sigma^s_B(k) = -g_{\sigma B}\langle\sigma\rangle + \frac{1}{4\pi^2 k}\int_0^{k_{F_{B'}}} \frac{q\, M^*_B(q)}{E^*_B(q)} \times \left[\frac{1}{4}g^2_{\sigma B'}\Theta_\sigma(k,q) - g^2_{\omega B'}\Theta_\omega(k,q)\right] dq$$

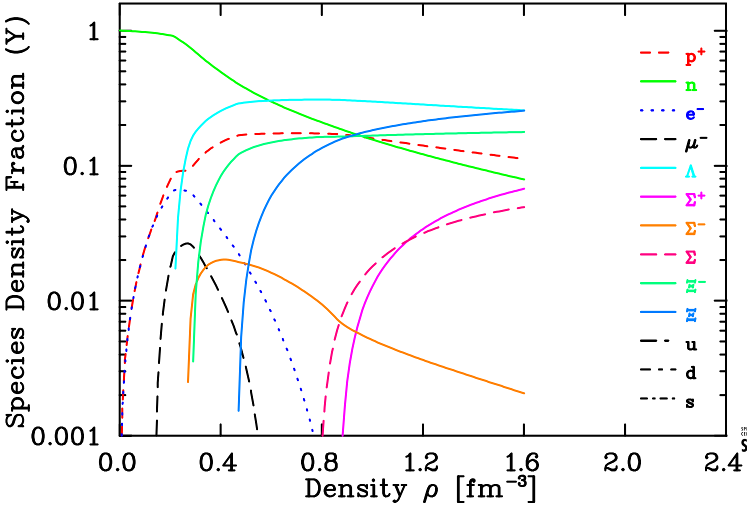
Hyperonic QMC
Hartree–Fock



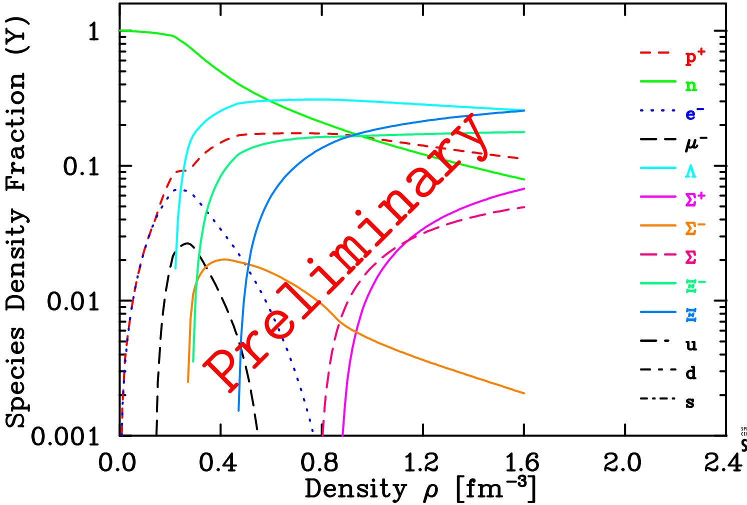
Hyperonic QMC
Hartree



Hyperonic QMC
Hartree–Fock



Hyperonic QMC
Hartree–Fock



Further Reading I

Carroll
Applications of the Octet Baryon Quark-Meson Coupling Model to Hybrid Stars (PhD Thesis).
arXiv:1001.4318

Carroll, Thomas
The Hyperfine, Hyperonic QMC Model - Extension to Hartree–Fock I: Infinite Nuclear Matter.
in preparation

Carroll, Leinweber, Williams, Thomas
Phase Transition from QMC Hyperonic Matter to Deconfined Quark Matter.
Phys.Rev.C79:045810, 2009
[doi:10.1103/PhysRevC.79.045810]

Further Reading II

Guichon, Thomas, Tsushima
Binding of hypernuclei in the latest quark-meson coupling model.
Nucl.Phys.A814:66-73, 2008
[doi:10.1016/j.nuclphysa.2008.10.001]

Rikovska-Stone, Guichon, Matevosyan, Thomas
Cold uniform matter and neutron stars in the quark-mesons-coupling model.
Nucl.Phys.A792:341-369, 2007
[doi:10.1016/j.nuclphysa.2007.05.011]

Thank You

Happy Birthday, Tony!

Thank You

Happy Birthday, Tony!

Thank You

Happy Birthday, Tony!

Thank You

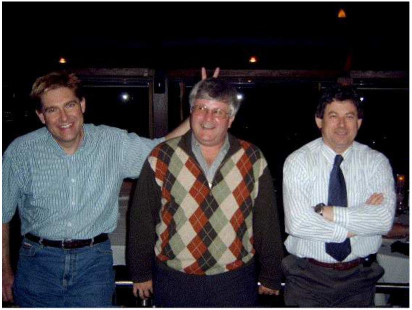
Happy Birthday, Tony!

Thank You

Happy Birthday, Tony!

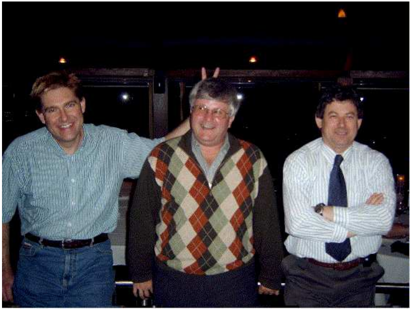
Thank You

Happy Birthday, Tony!



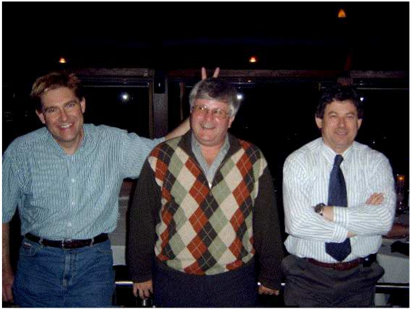
Thank You

Happy Birthday, Tony!



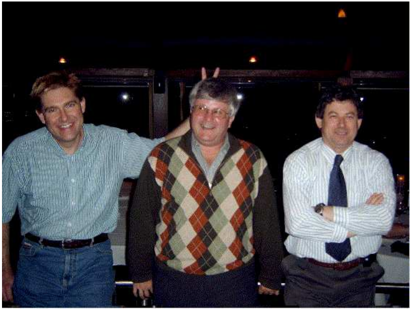
Thank You

Happy Birthday, Tony!



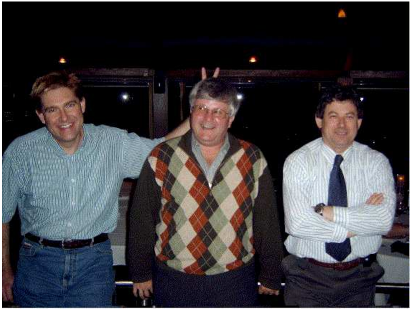
Thank You

Happy Birthday, Tony!



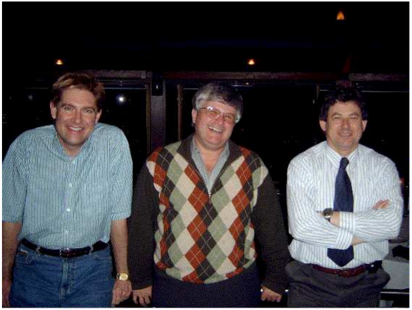
Thank You

Happy Birthday, Tony!



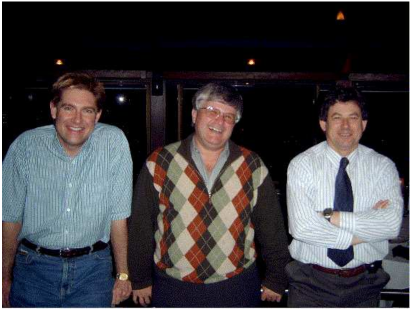
Thank You

Happy Birthday, Tony!



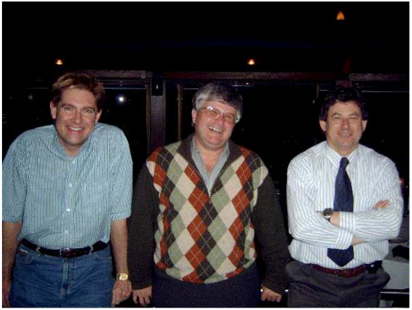
Thank You

Happy Birthday, Tony!



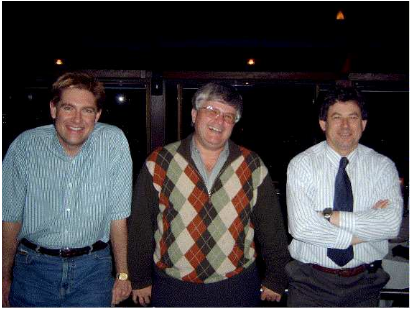
Thank You

Happy Birthday, Tony!



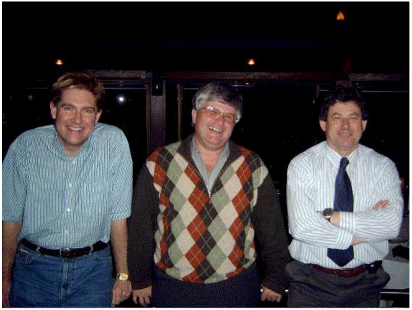
Thank You

Happy Birthday, Tony!



Thank You

Happy Birthday, Tony!



Thank You

Happy Birthday, Tony!

Thank You

Happy Birthday, Tony!

Thank You

Happy Birthday, Tony!

Thank You

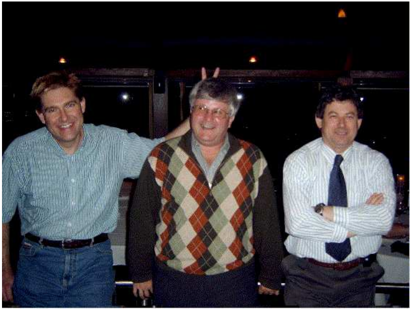
Happy Birthday, Tony!

Thank You

Happy Birthday, Tony!

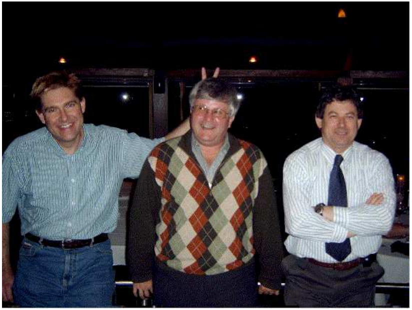
Thank You

Happy Birthday, Tony!



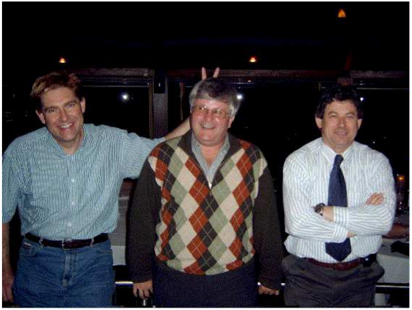
Thank You

Happy Birthday, Tony!



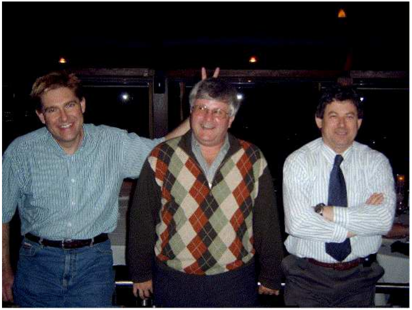
Thank You

Happy Birthday, Tony!



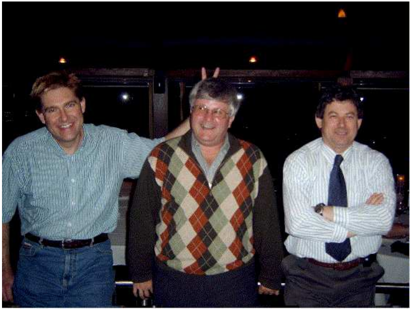
Thank You

Happy Birthday, Tony!



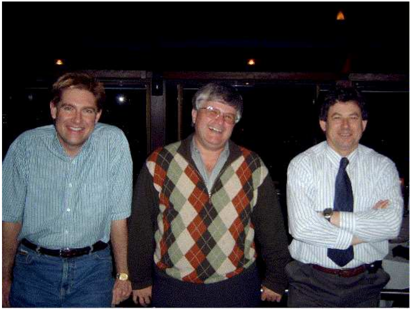
Thank You

Happy Birthday, Tony!



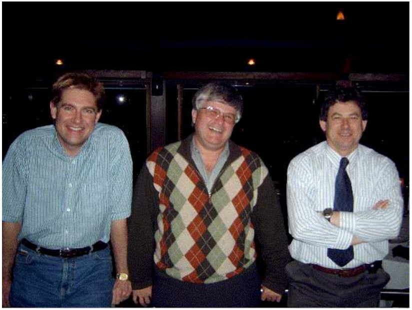
Thank You

Happy Birthday, Tony!



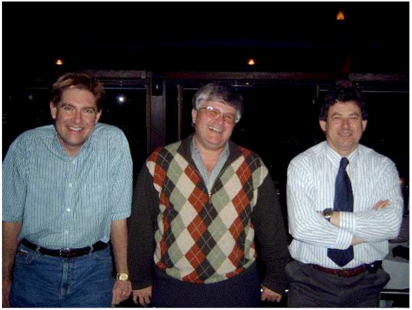
Thank You

Happy Birthday, Tony!



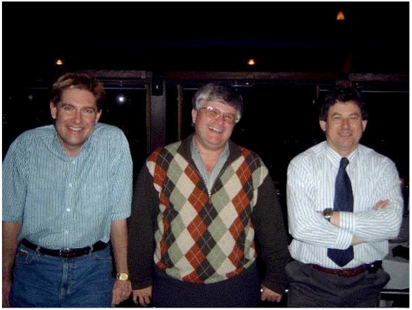
Thank You

Happy Birthday, Tony!



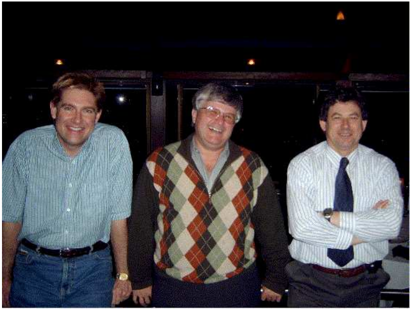
Thank You

Happy Birthday, Tony!



Thank You

Happy Birthday, Tony!



Thank You

Happy Birthday, Tony!

Thank You

Happy Birthday, Tony!

Thank You

Happy Birthday, Tony!

Thank You

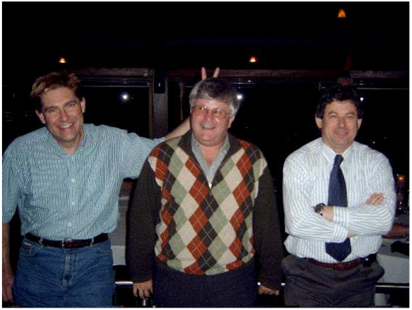
Happy Birthday, Tony!

Thank You

Happy Birthday, Tony!

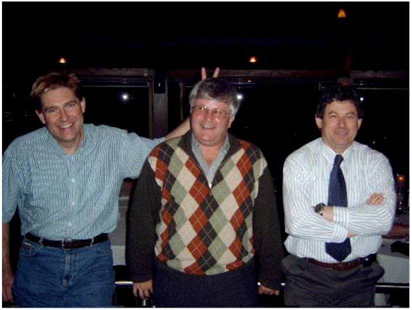
Thank You

Happy Birthday, Tony!



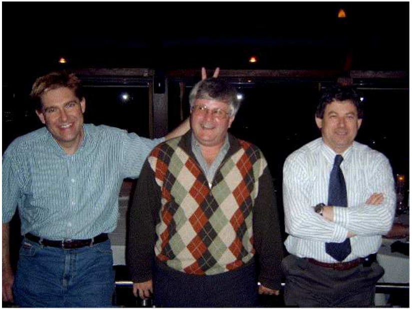
Thank You

Happy Birthday, Tony!



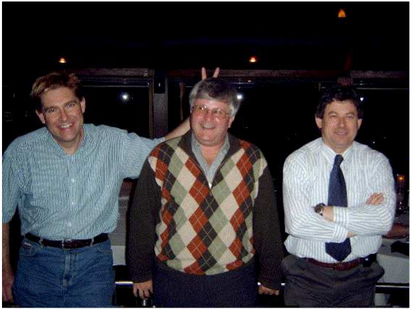
Thank You

Happy Birthday, Tony!



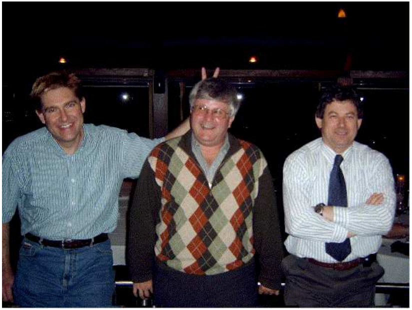
Thank You

Happy Birthday, Tony!



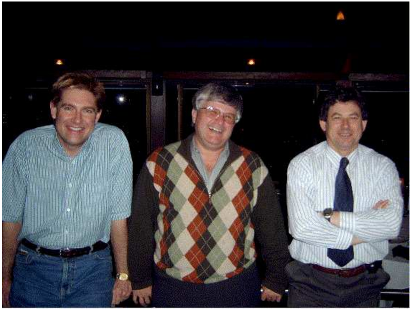
Thank You

Happy Birthday, Tony!



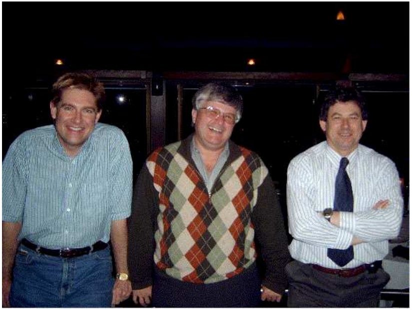
Thank You

Happy Birthday, Tony!



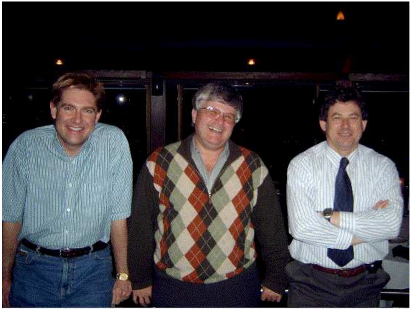
Thank You

Happy Birthday, Tony!



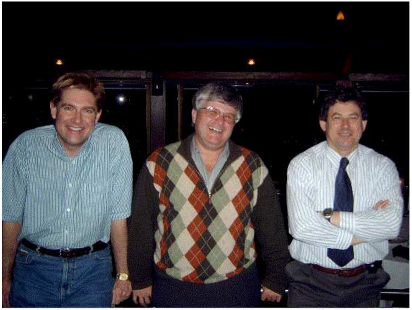
Thank You

Happy Birthday, Tony!



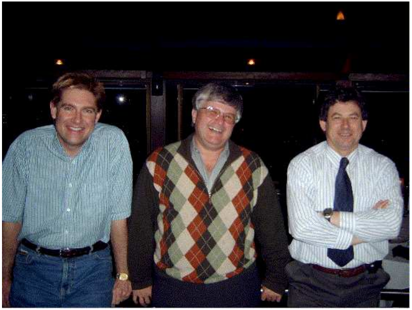
Thank You

Happy Birthday, Tony!



Thank You

Happy Birthday, Tony!



Thank You

Happy Birthday, Tony!

Cheers, Everyone!