Chiral Symmetry Restoration and Deconfinement in Neutron Stars

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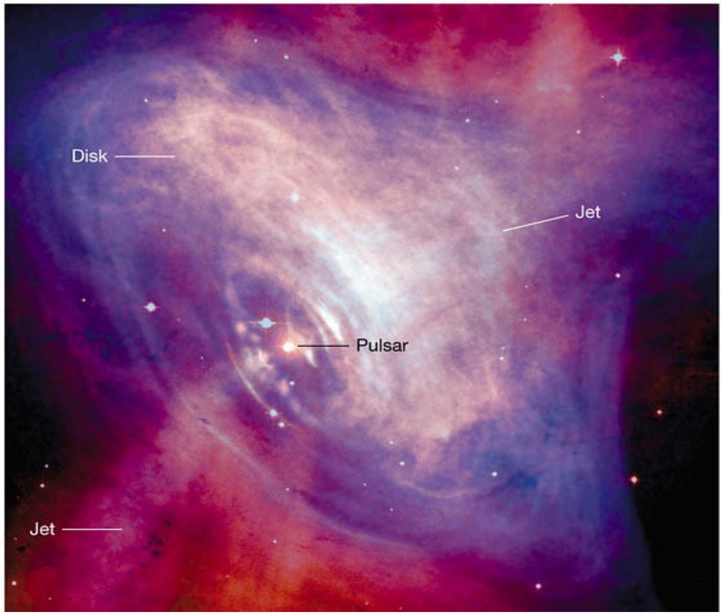


The Crab Pulsar. This image combines optical data from Hubble (in red) and X-ray images from Chandra X-ray Observatory (in blue).

1. Motivation

- Having a model that can be used for:
  - small temperatures and high densities

    neutron stars

  - high temperatures and small densities

    heavy ion collisions

  - everything in the middle

- Study the effect of finite temperature and entropy in chiral symmetry restoration and deconfinement inside proto-neutron stars

2. General Features of Neutron Stars

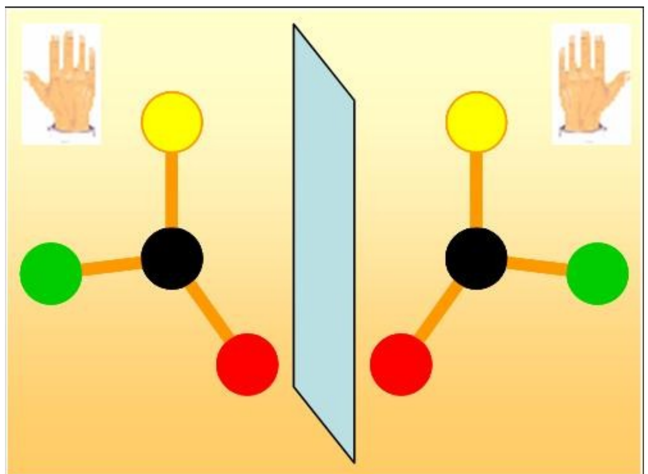
- Mass: $M \sim 1 - 2\ M_{\odot}$ (solar masses)
- Radius: $R \sim 10$ km
- Density: $\rho \sim 10^{15}$ g/cm^3

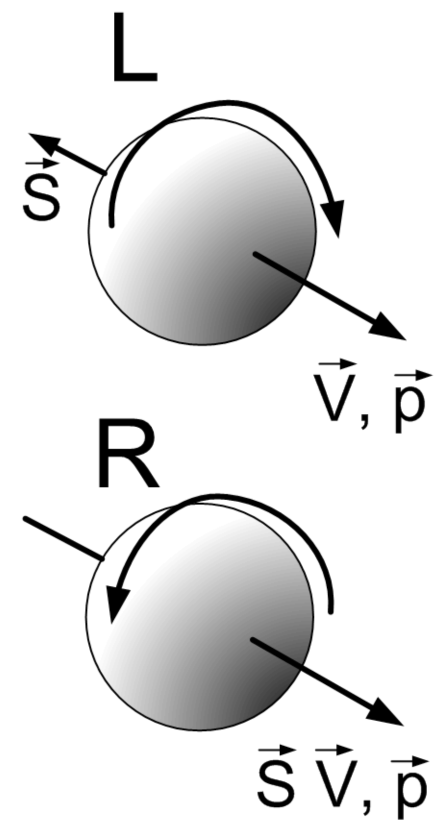
Mass of Earth on 1/100 of Manhattan area

- Temperature: 1 MeV (neutron star), up to 50 MeV (proto-neutron star)

1 MeV= 11.6 GigaKelvin

3. Introduction to Chiral Models





$$\Psi = \Psi_L + \Psi_R$$

$$\Psi_L = 1/2(1-\gamma_5)\Psi \quad \text{and} \quad \Psi_R = 1/2(1+\gamma_5)\Psi$$

Particle description

Walecka type Lagrangian density:

$$\mathscr{L}=\bar{\Psi}(i\gamma^{\mu}\partial_{\mu}-M)\Psi+\bar{\Psi}(g_{\sigma}\sigma+g_{\omega}\gamma^{\mu}\omega_{\mu})\Psi+\mathscr{L}(\sigma)+\mathscr{L}(\omega)$$

$$\bar{\Psi}\gamma^{\mu}\omega_{\mu}\Psi$$

vector term

preserves symmetry

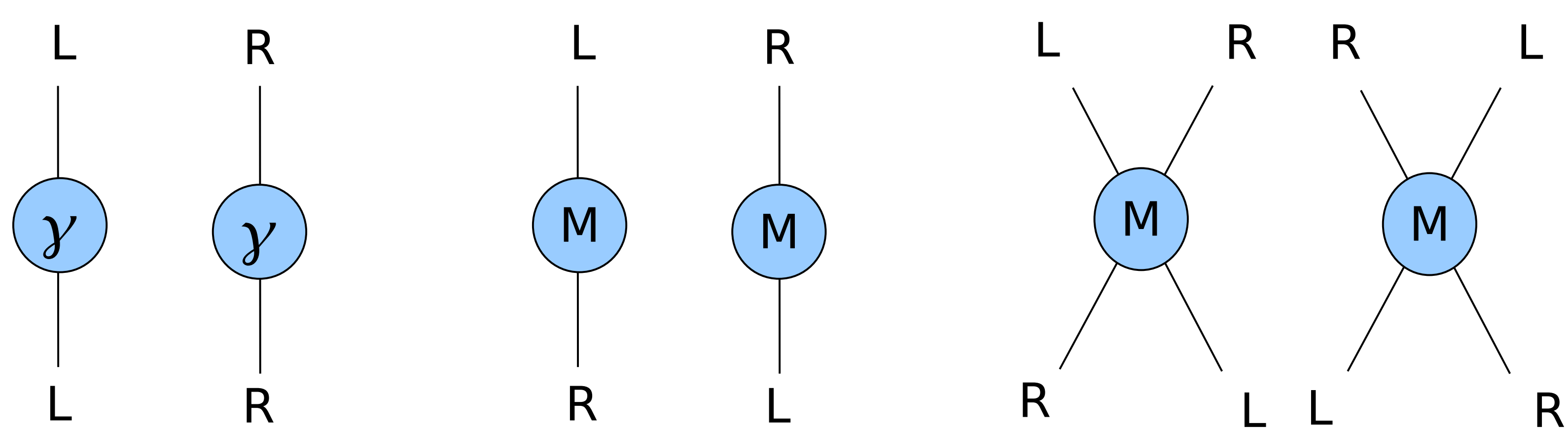
$$\bar{\Psi}M\Psi$$

scalar term

breaks symmetry

$$(\bar{\Psi}\Psi)^2+(\bar{\Psi}i\gamma_5\Psi)^2$$

preserves symmetry



Chiral invariant

$(\bar{\Psi}\Psi)^2+(\bar{\Psi}i\gamma_5\Psi)^2$

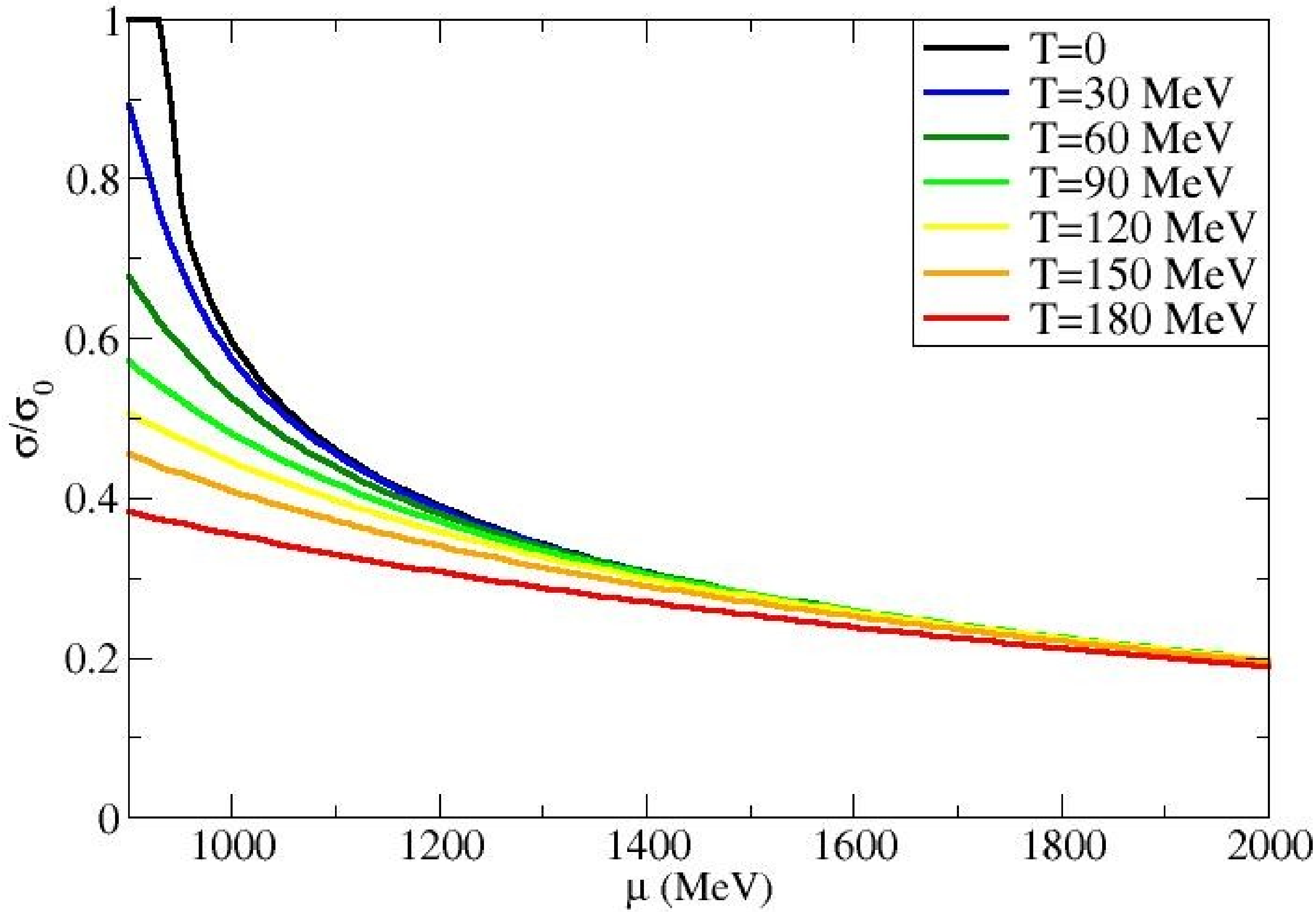
$<\bar{\Psi}\Psi> \rightarrow \sigma$ $\quad$ $<\bar{\Psi}i\gamma_5\Psi> \rightarrow \boldsymbol{\pi}$

- Effective mass come from coupling to field

$$\bar{\Psi}M^*\Psi \qquad M^*=g_\sigma \sigma$$

- QCD vacuum filled with $\bar{q}q$ pairs (not chiral invariant!)

Chiral Condensate $\sigma\ (\mu_B, T)$



The chiral symmetry is restored before (smaller chemical potential) for higher temperatures.

4. Non-linear Realization of Sigma Model

- allows heavy degrees of freedom to transform equally under left and right chiral transformations
- ensures chiral invariance for heavy particles if their coupling is invariant under local $SU(3)_V$ transformations
- respects properties of underlying theory: QCD
  - spontaneous chiral symmetry breaking
  - axial U(1) anomaly
  - trace anomaly

$$U(3)_L \times U(3)_R = SU(3)_L \times SU(3)_R \times U(1)_V \times U(1)_A = SU(3)_V \times U(1)_V$$

$$L_{MFT} = L_{Kin} + L_{Bscal} + L_{Bvec} + L_{scal} + L_{vec} + L_{SB}$$

$$L_{Bscal} + L_{Bvec} = -\sum_i \bar{\psi}_i [g_{i\omega}\gamma_0\omega + g_{i\phi}\gamma_0\phi + g_{i\rho}\gamma_0\tau_3\rho + m_i^*]\psi_i$$

$$L_{vec} = -\frac{1}{2}(m_\omega^2\omega^2 + m_\rho^2\rho^2 + m_\phi^2\phi^2)\frac{\chi^2}{\chi_o^2} - g_4\left(\omega^4 + \frac{\phi^4}{4} + 3\omega^2\phi^2 + \frac{4\omega^3\phi}{\sqrt{2}} + \frac{2\omega\phi^3}{\sqrt{2}}\right)$$

$$L_{scal} = \frac{1}{2}k_0\chi^2(\sigma^2 + \zeta^2 + \delta^2) - k_1(\sigma^2 + \zeta^2 + \delta^2)^2 - k_2\left(\frac{\sigma^4}{2} + \frac{\delta^4}{2} + 3\sigma^2\delta^2 + \zeta^4\right)$$

$$-k_3\chi(\sigma^2 - \delta^2)\zeta + k_4\chi^4 + \frac{1}{4}\chi^4 \ln\frac{\chi^4}{\chi_0^4} - \epsilon \ \chi^4 \ln\frac{(\sigma^2 - \delta^2)\zeta}{\sigma_0^2\zeta_0}$$

$$L_{SB} = \left(\frac{\chi}{\chi_0}\right)^2 \left[m_\pi^2 f_\pi \sigma + \left(\sqrt{2}m_k^2 f_k - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\right)\zeta\right]$$

$$m^* = g_{i\sigma}\sigma + g_{i\delta}\tau_3\delta + g_{i\zeta}\zeta + \delta m$$

frozen limit:
$\chi = \chi_0$

5. Neutron Stars

- Hadronic degrees of freedom

$p, n, \Lambda, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^0, \Xi^-$

$\Delta^{++}, \Delta^+, \Delta^0, \Delta^-, \Sigma^{*+}, \Sigma^{*0}, \Sigma^{*-}, \Xi^{*0}, \Xi^{*-}, \Omega$

e, μ

ω, ϕ, ρ

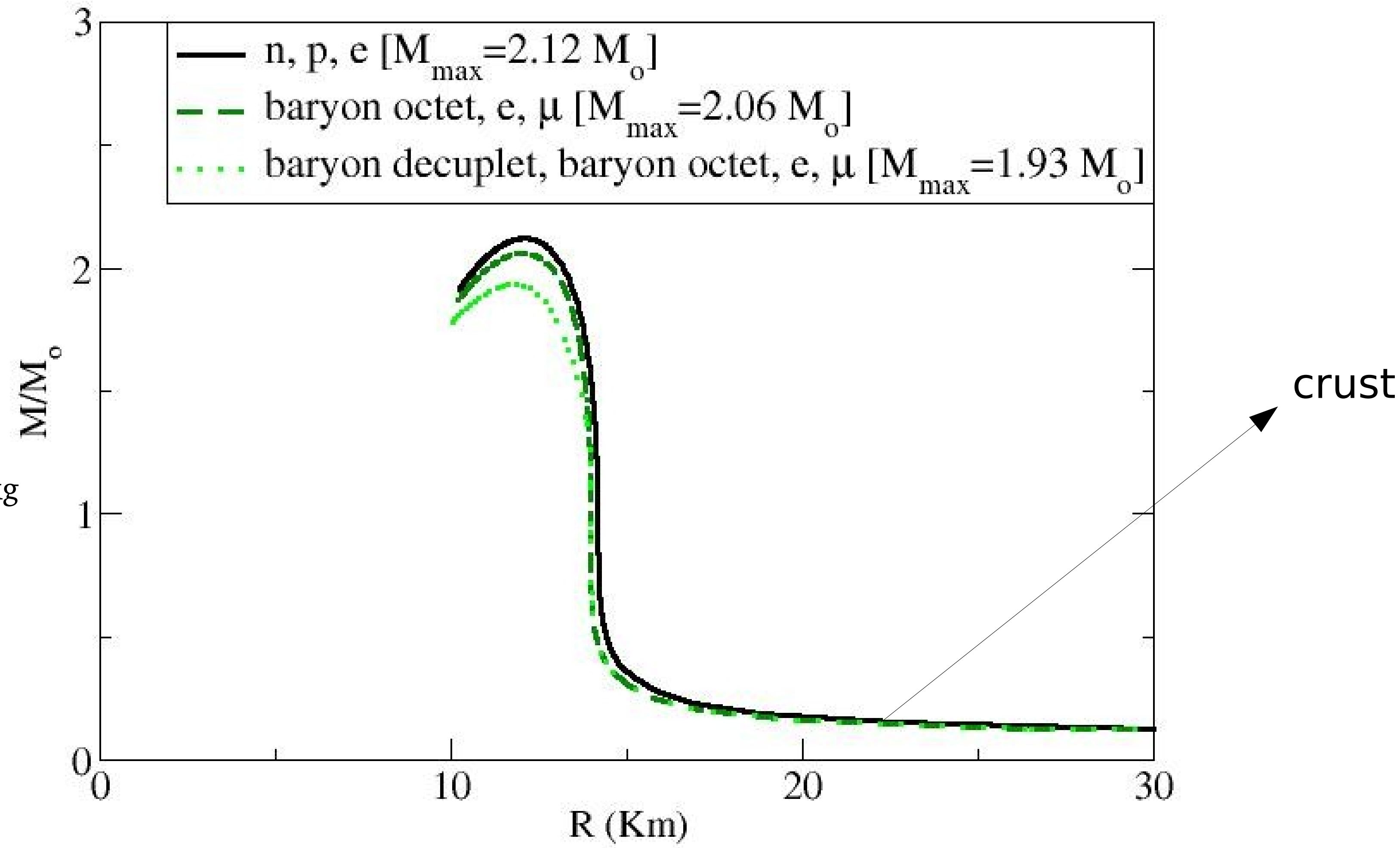
$\sigma, \zeta, \delta, \chi$

- Charge Neutrality
- Chemical Equilibrium

$$n \leftrightarrow p + e + \bar{\nu}_e$$

Mass-Radius Diagram (TOV)

$M_\odot = 2 \times 10^{30}$ kg



Champion et al. (2008) J1903+0327 e-Print: astro-ph/08052396 **1.74±0.04**$M_\odot$

The new degrees of freedom decrease the neutron star mass.

6. Proto-Neutron Stars

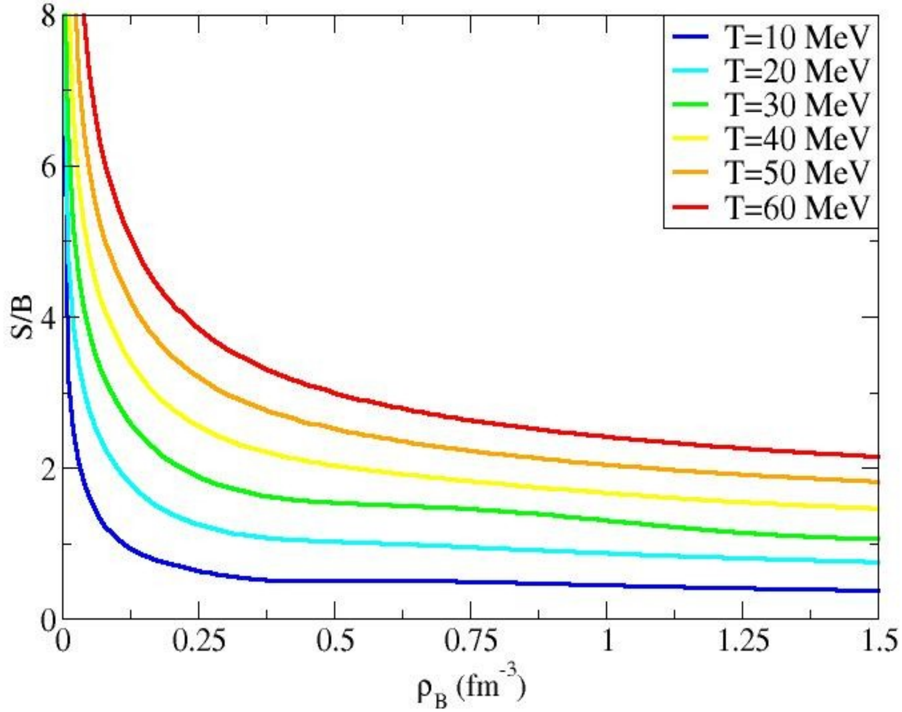
- Finite temperature
- A fixed entropy per baryon allows the temperature to increase towards the center of the star

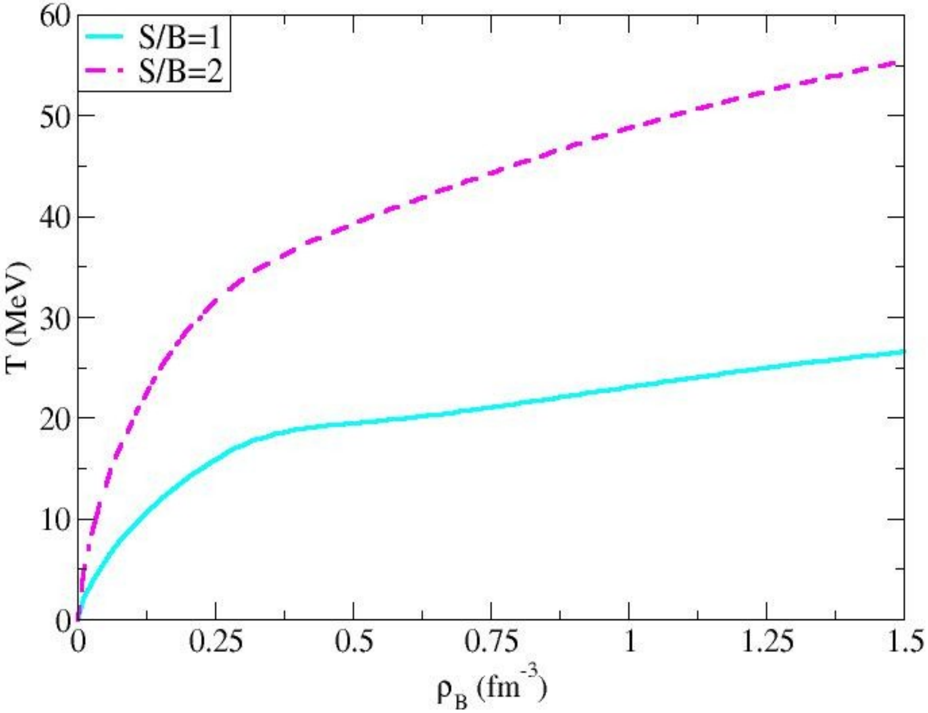
$T=0 \rightarrow 50$ MeV

- The maximum mass of the star increases with entropy
- No beta equilibrium
- The maximum mass of the star decreases with lepton number

$$Y_l = \frac{\rho_e + \rho_{\nu_e}}{\rho_B}$$

Fixed Temperature x Fixed Entropy/B





The entropy per baryon is approximately constant for a given temperature for large densities

The temperature increases with density for a given entropy per baryon

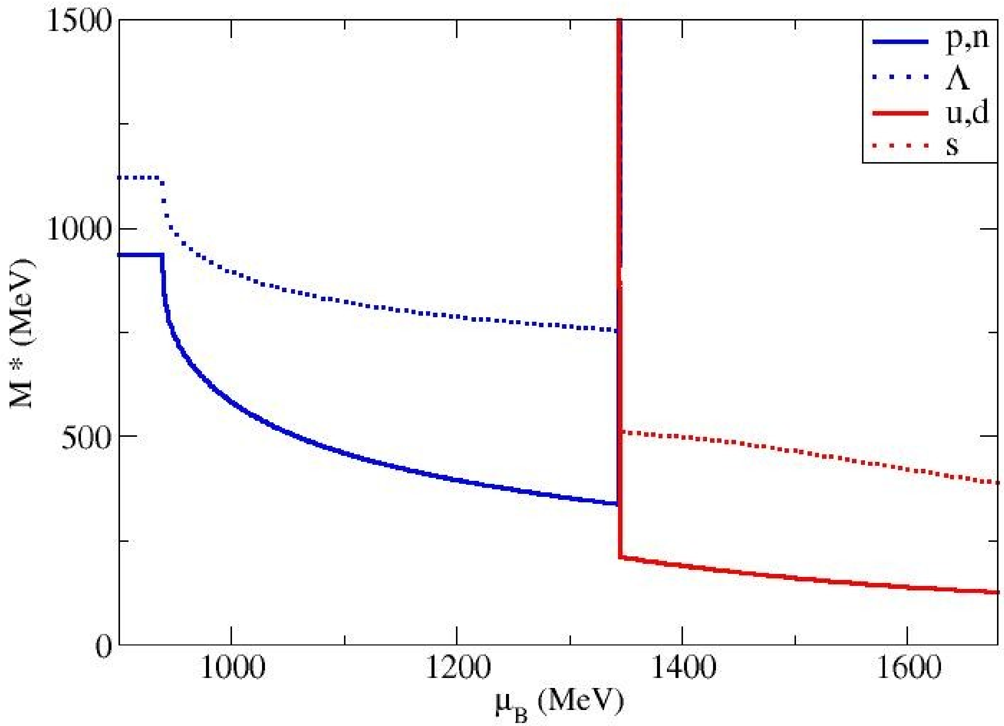
7. Deconfinement

- Same model for quarks hadrons

$$m_b^* = g_{b\sigma}\sigma + g_{b\delta}\tau_3\delta + g_{b\zeta}\zeta + \delta m_b + g_{b\Phi}\Phi^2$$

$$m_q^* = g_{q\sigma}\sigma + g_{q\delta}\tau_3\delta + g_{q\zeta}\zeta + \delta m_q + g_{q\Phi}(1-\Phi)$$

order parameter



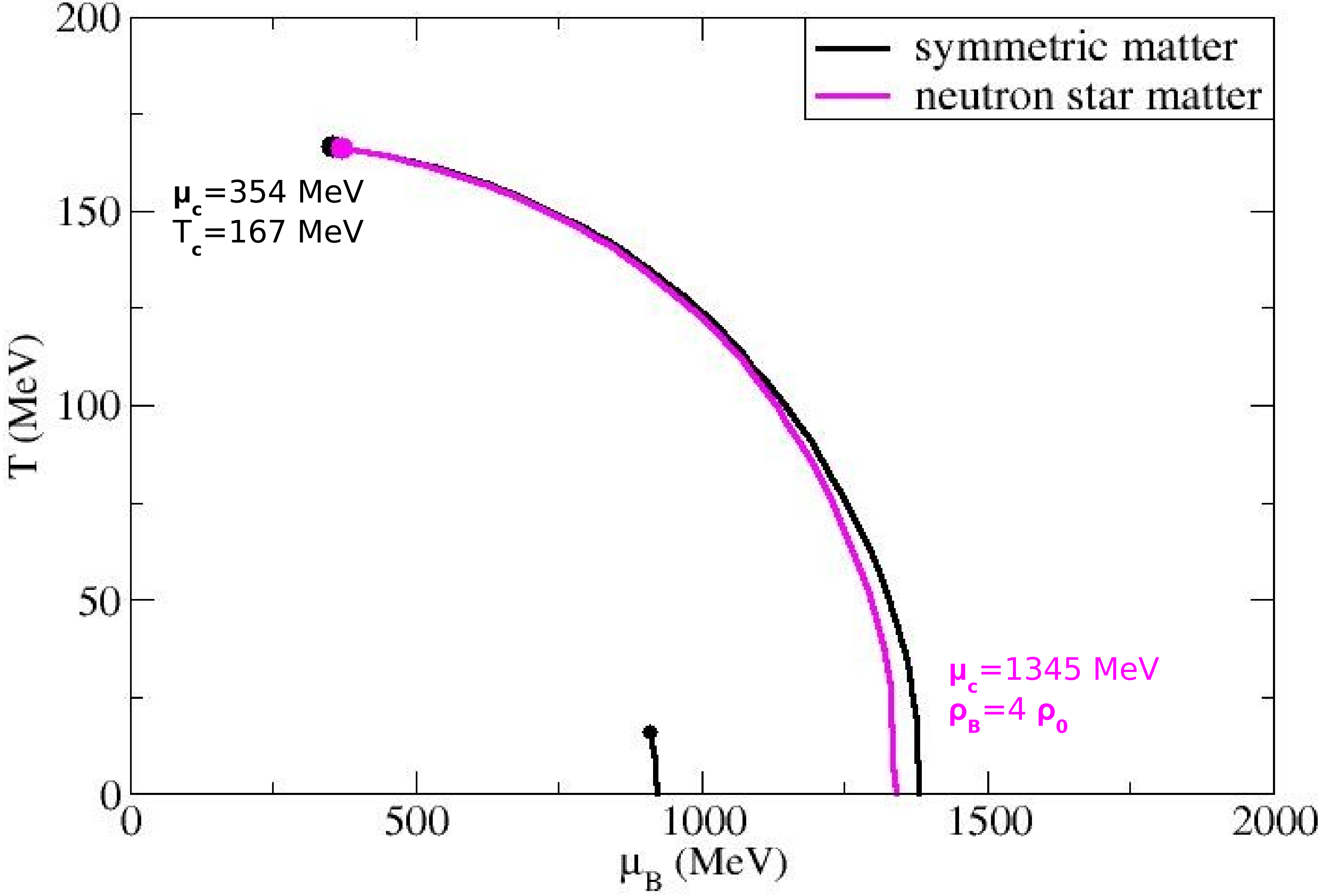
Ratti et al. Phys.Rev. D73:014019,2006

Ratti et al. Phys.Rev. D75:034007,2007

$$U = (a_0\, T^4 + a_1\, \mu^4 + a_2\, T^2\mu^2)\phi^2 + a_3\, T_0^4\, \ln(1 - 6\phi^2 + 8\phi^3 - 3\phi^4)$$

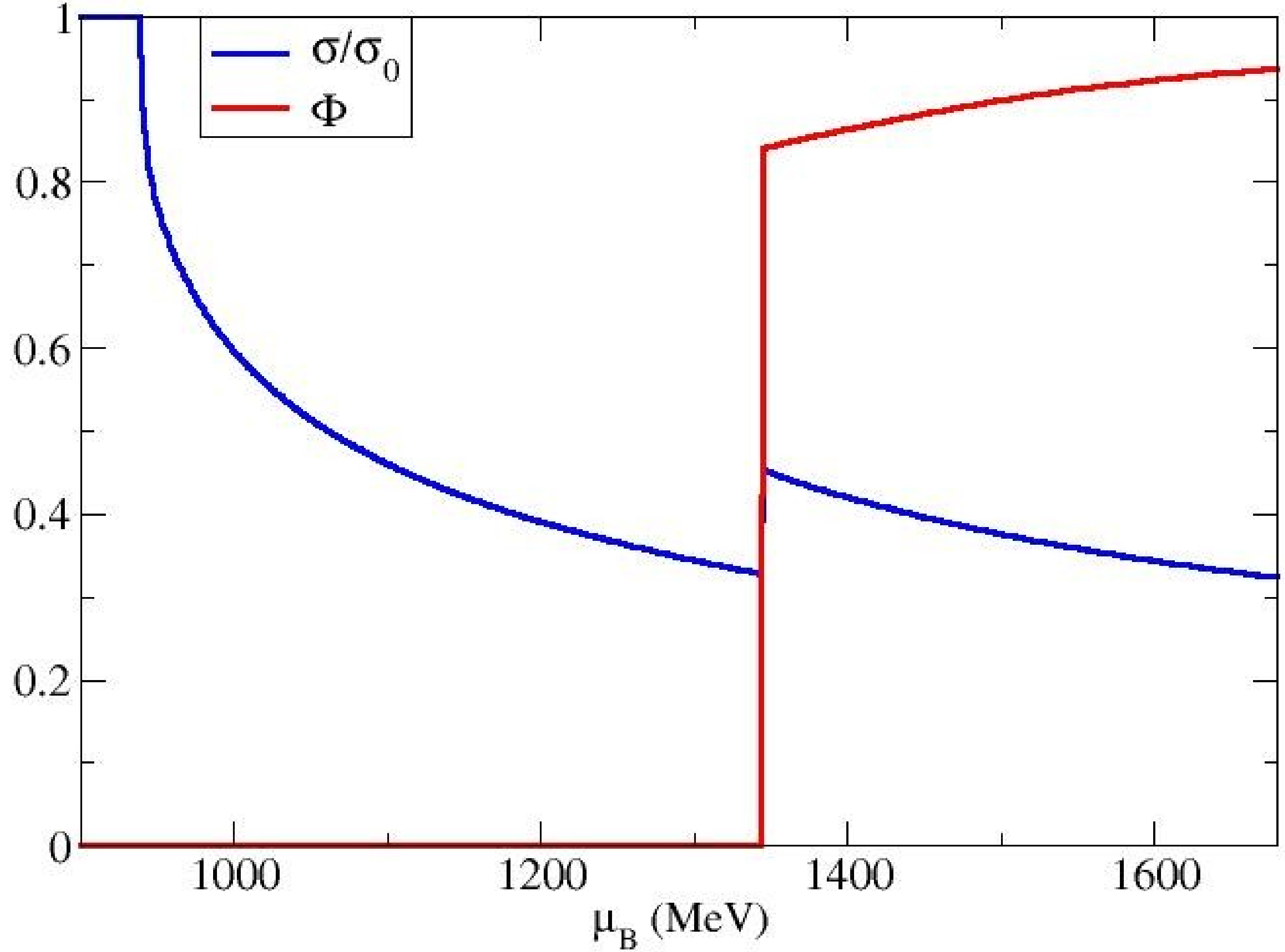
270/200 MeV

8. Phase Diagram



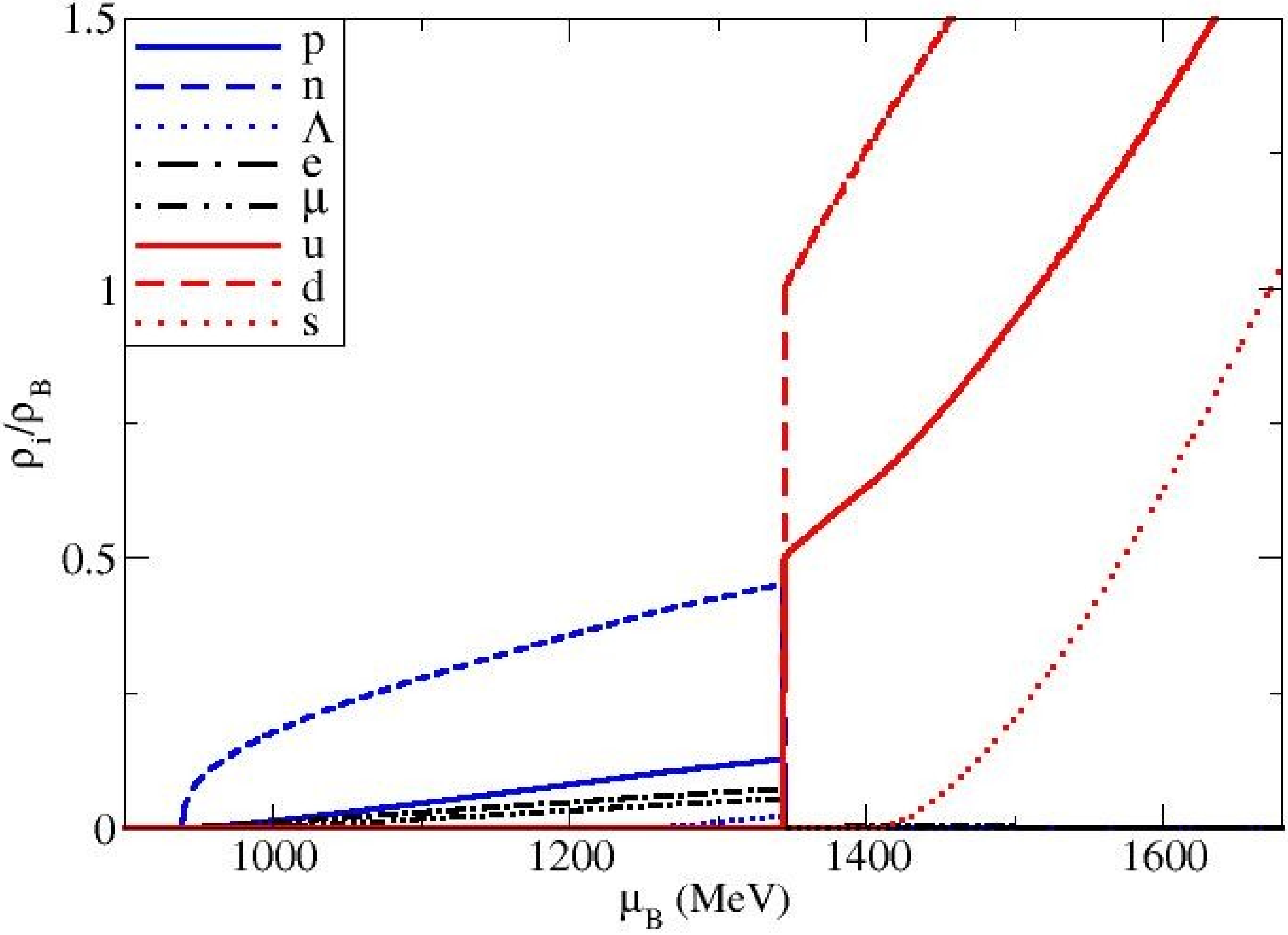
The first order phase transition line ends up on a critical point.

9. Hybrid Stars   T=0



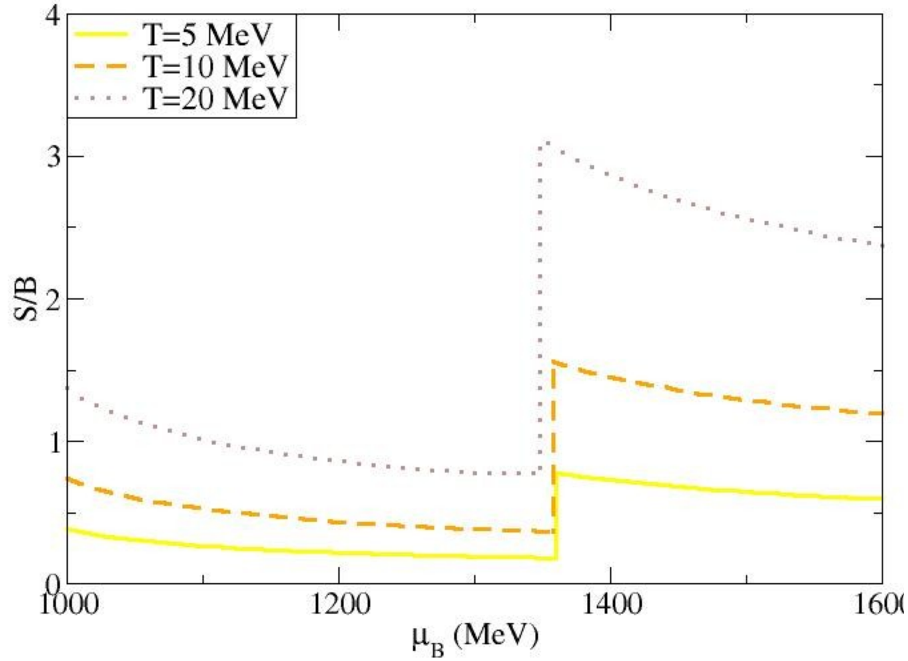
First order phase transition for the Polyakov field and the chiral condensate.

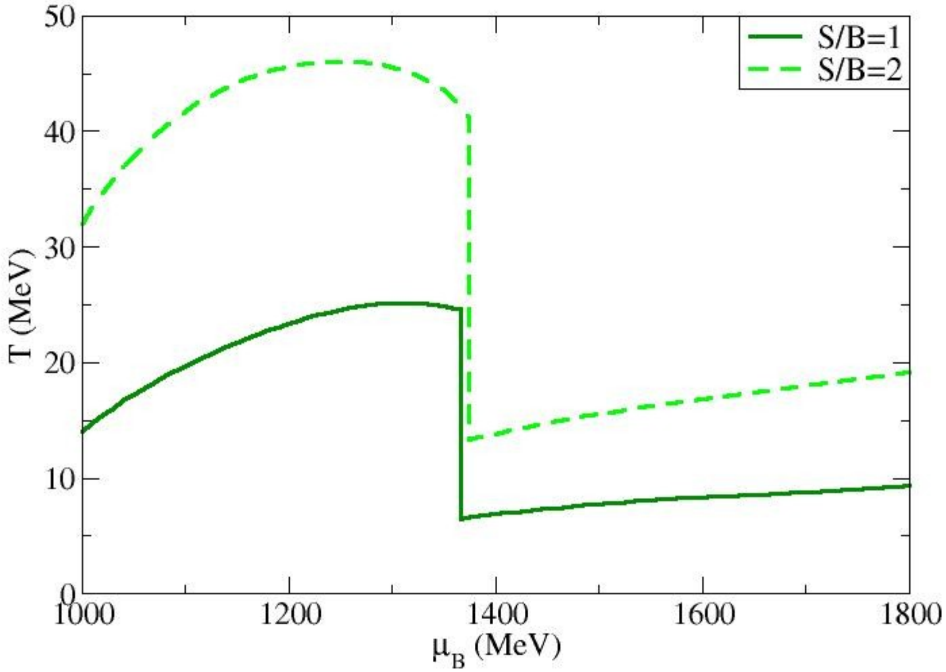
Population (local charge neutrality)



No mixed phase: just hadron matter or quark matter.

Fixed Temperature x Fixed Entropy/B

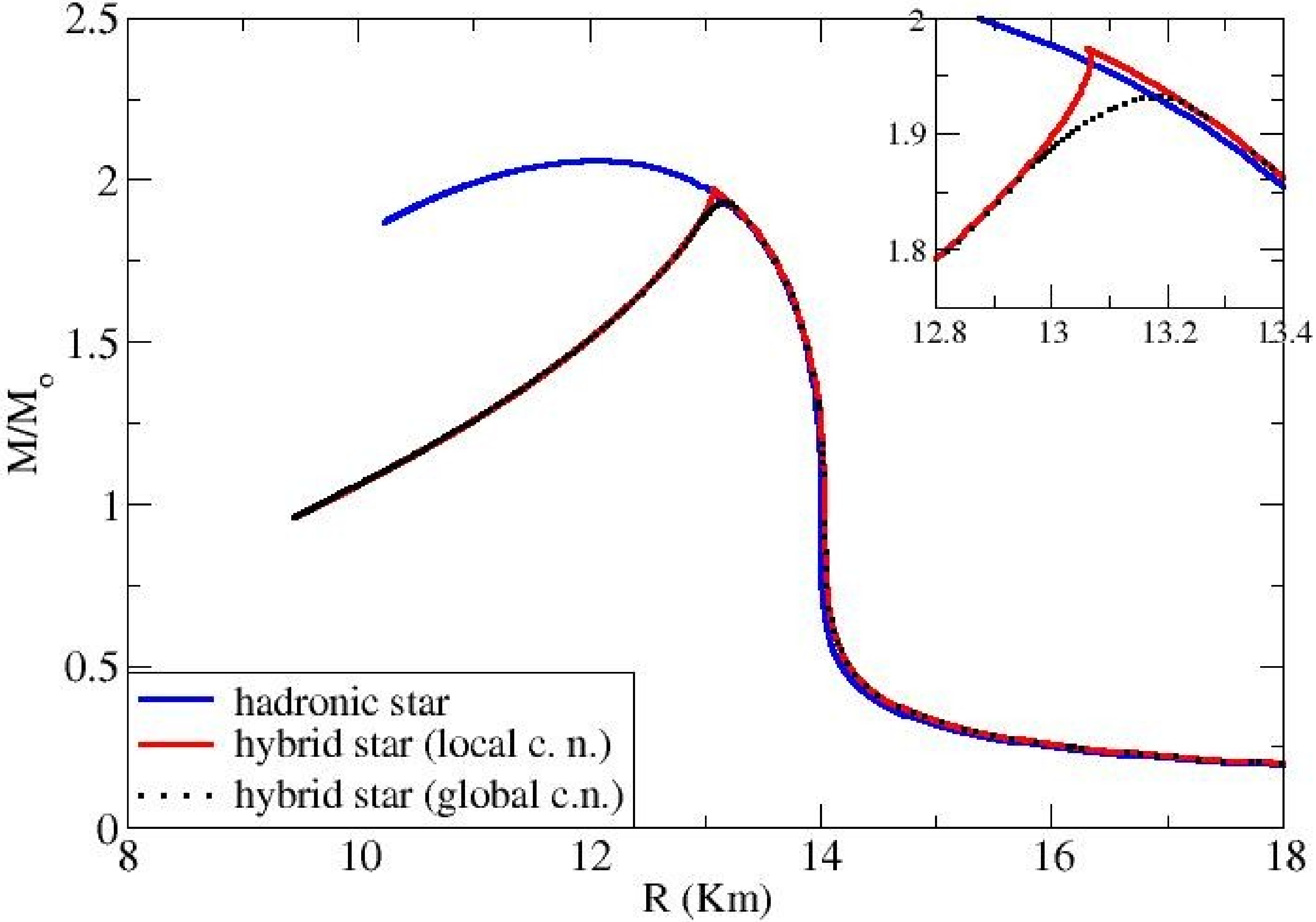




There is a jump in the entropy per baryon to values 3 times higher

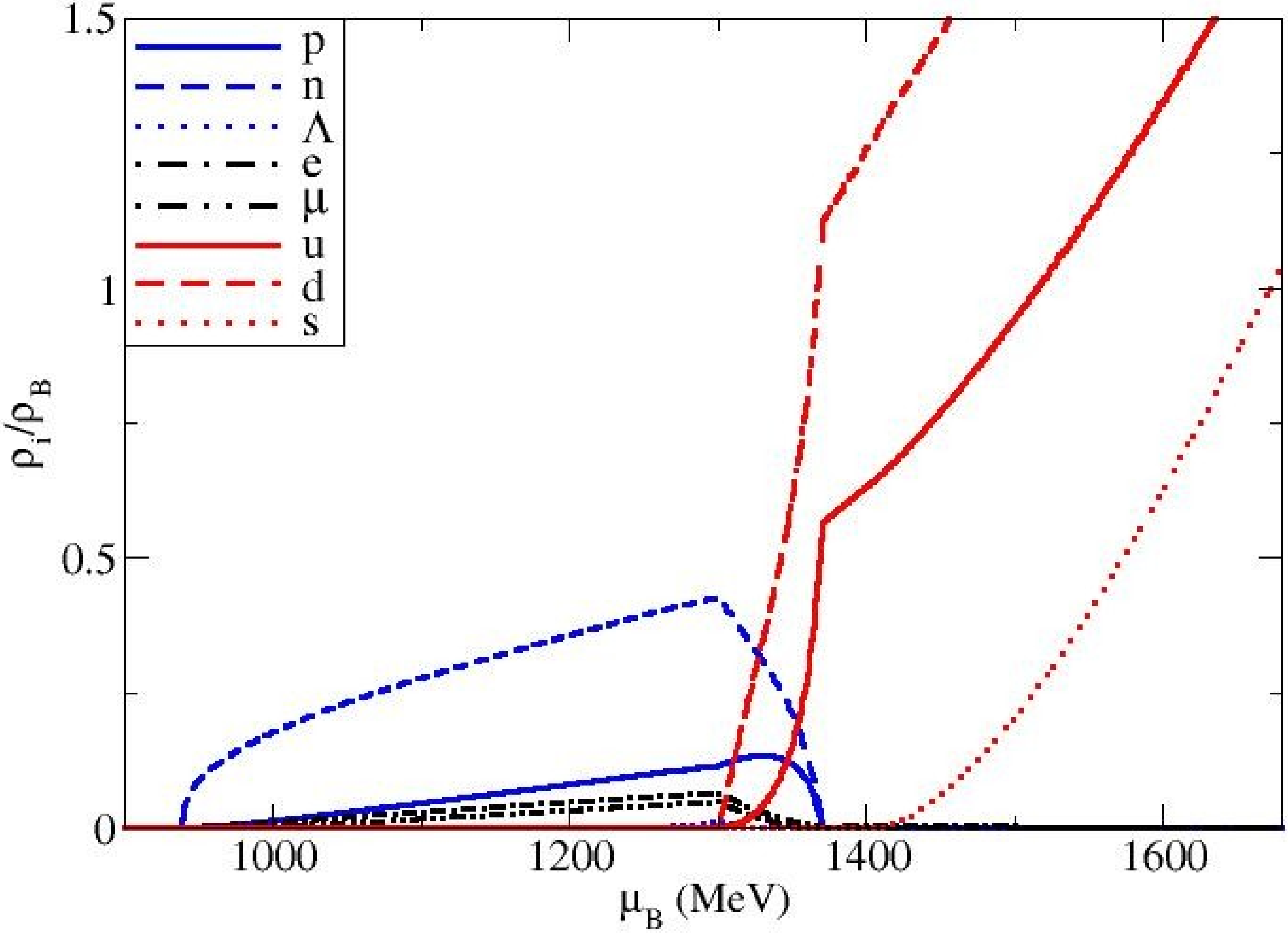
There is a jump in the temperature to values 3 times smaller

Mass-Radius Diagram



With the inclusion of a quark phase the maximum mass of the star decreases from 2.1 to 1.9$M_\odot$.

Population (global charge neutrality)



Presence of mixed phase.

10. Conclusions

- Observed that chiral symmetry is partially restored inside neutron stars and the transition is a cross over

- Analysed possible compositions for neutron stars

- Studied the effect of temperature, entropy and lepton number on proto-neutron stars

- Extended the chiral model to include quarks and calibrated the new potential to reproduce low density/high temperature physics
- Concluded that local charge neutrality at zero temperature reproduces 2 distinct phases (no mixing) and the deconfinement to quark matter makes the star unstable
- Concluded that global charge neutrality at zero temperature reproduces a mixed phase that allows stable star configurations with presence of hybrid matter up to 2 km

Outlook

- Apply the extended chiral model to intermediate temperatures and densities
- Apply the chiral model to supernova simulations
- Study different couplings and potentials to the Polyakov loop looking for stable quark matter
- Find observables that can be used to show the existence of quark matter inside stars