# Chiral Symmetry Restoration and Deconfinement in Neutron Stars

Verônica Dexheimer

Gettysburg College

FIAS Frankfurt Institute for Advanced Studies

HIC for FAIR

# 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

- Include different degrees of freedom in the same model

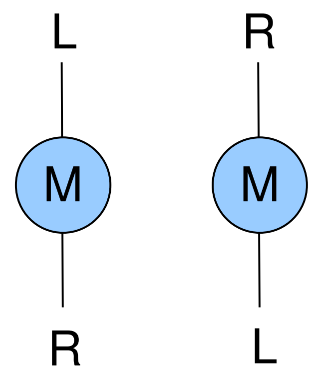
- Study chiral symmetry restoration and deconfinement to quark matter inside compact stars

# 2. Chiral Model

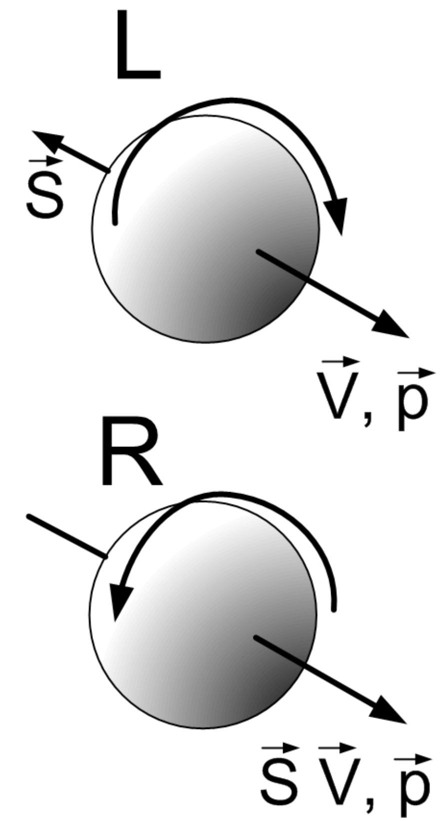
$\bar{\Psi} M \Psi$

scalar term

breaks symmetry




$\langle \bar{\Psi}\Psi \rangle \to \sigma$

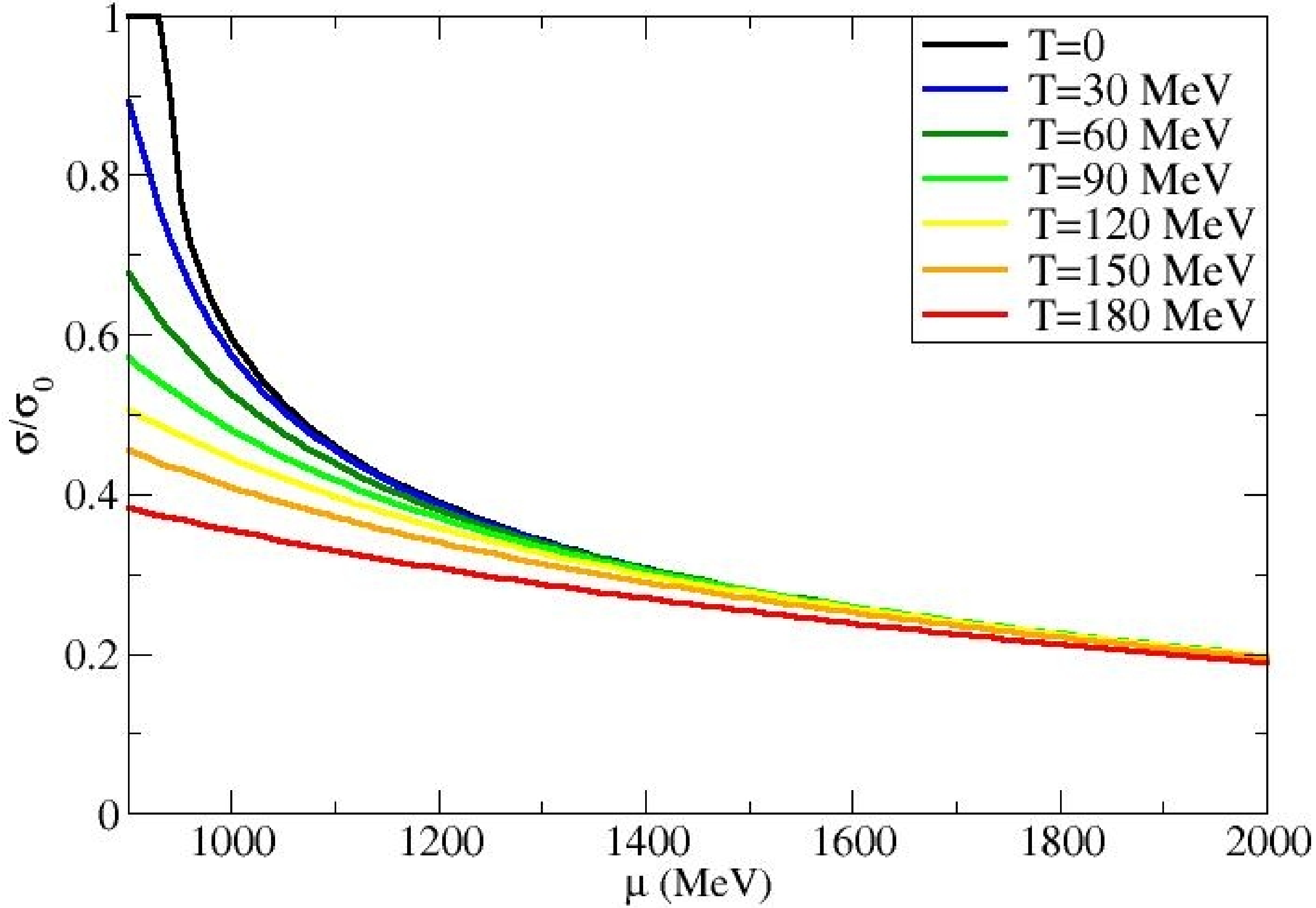



☆ Effective mass comes from coupling to field

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

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

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




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

# 3. Composition

- Appearance of heavier (strange) particles as density increases

$p,\ n,\ \Lambda,\ \Sigma^{+},\ \Sigma^{0},\ \Sigma^{-},\ \Xi^{0},\ \Xi^{-}$ → hyperons

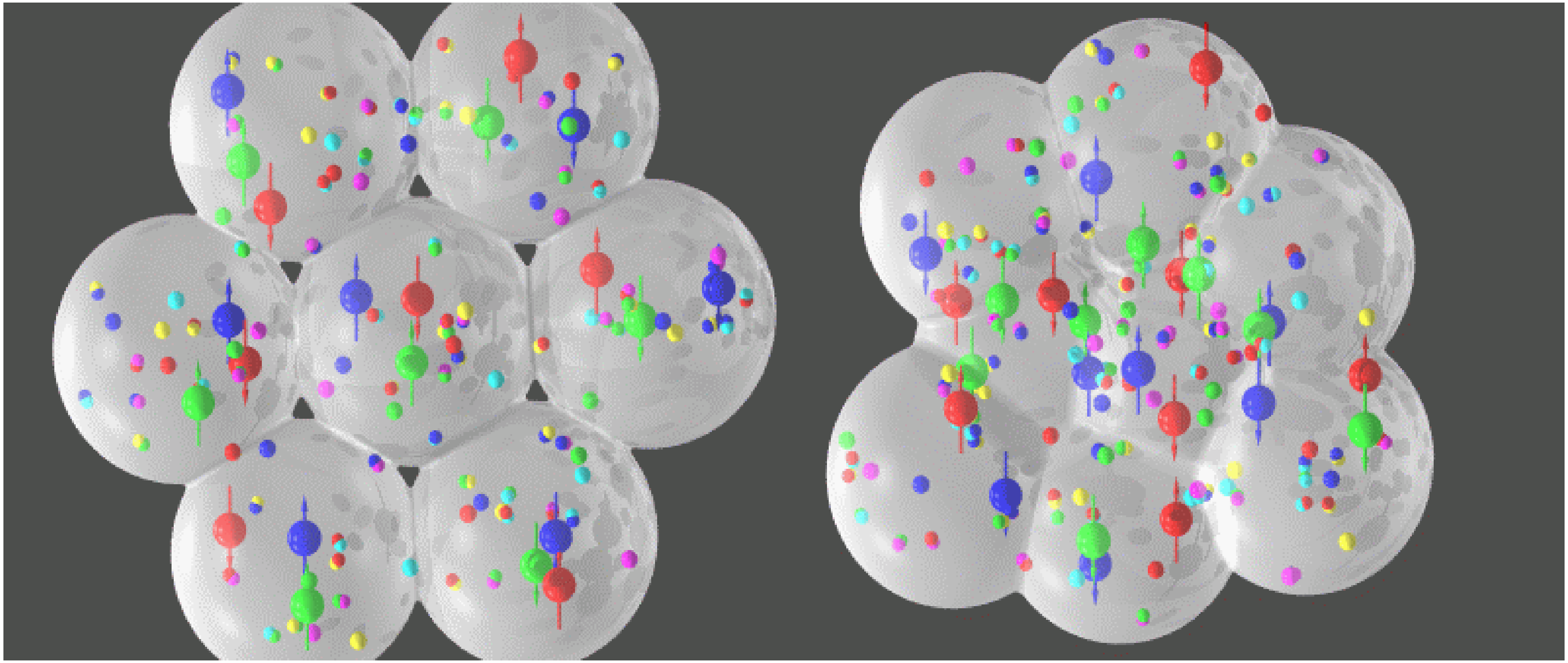
$\Delta^{++},\ \Delta^{+},\ \Delta^{0},\ \Delta^{-},\ \Sigma^{*+},\ \Sigma^{*0},\ \Sigma^{*-},\ \Xi^{*0},\ \Xi^{*-},\ \Omega$

- Amount of each particle not constant
- Chemical equilibrium

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

- Leptons ensure charge neutrality $e,\ \mu$

- Deconfinement of hadrons



increase of density $\rho_B$

- New degrees of freedom: quarks **u, d, s**
- Chiral symmetry restoration

# 4. Non Linear Sigma Model (hadrons)

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

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

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

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

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

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

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

frozen limit:
$\chi = \chi_0$

# 5. Inclusion of Quarks in the Model

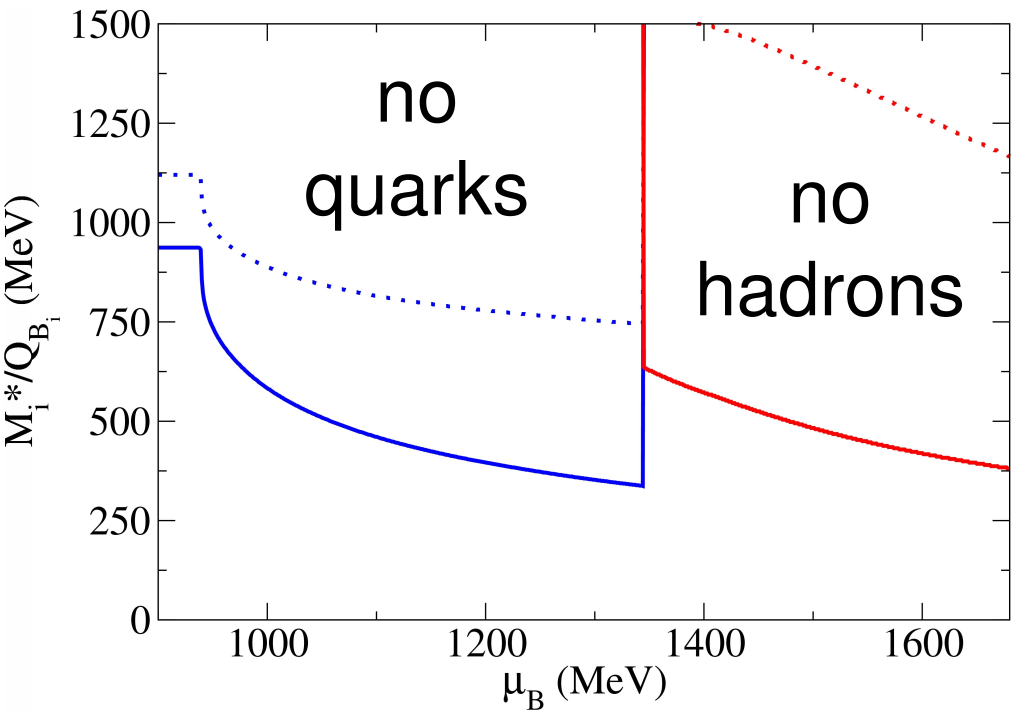
- Same model for hadrons and quarks

mesons

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

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

order parameter for deconfinement
in analogy with the Polyakov loop

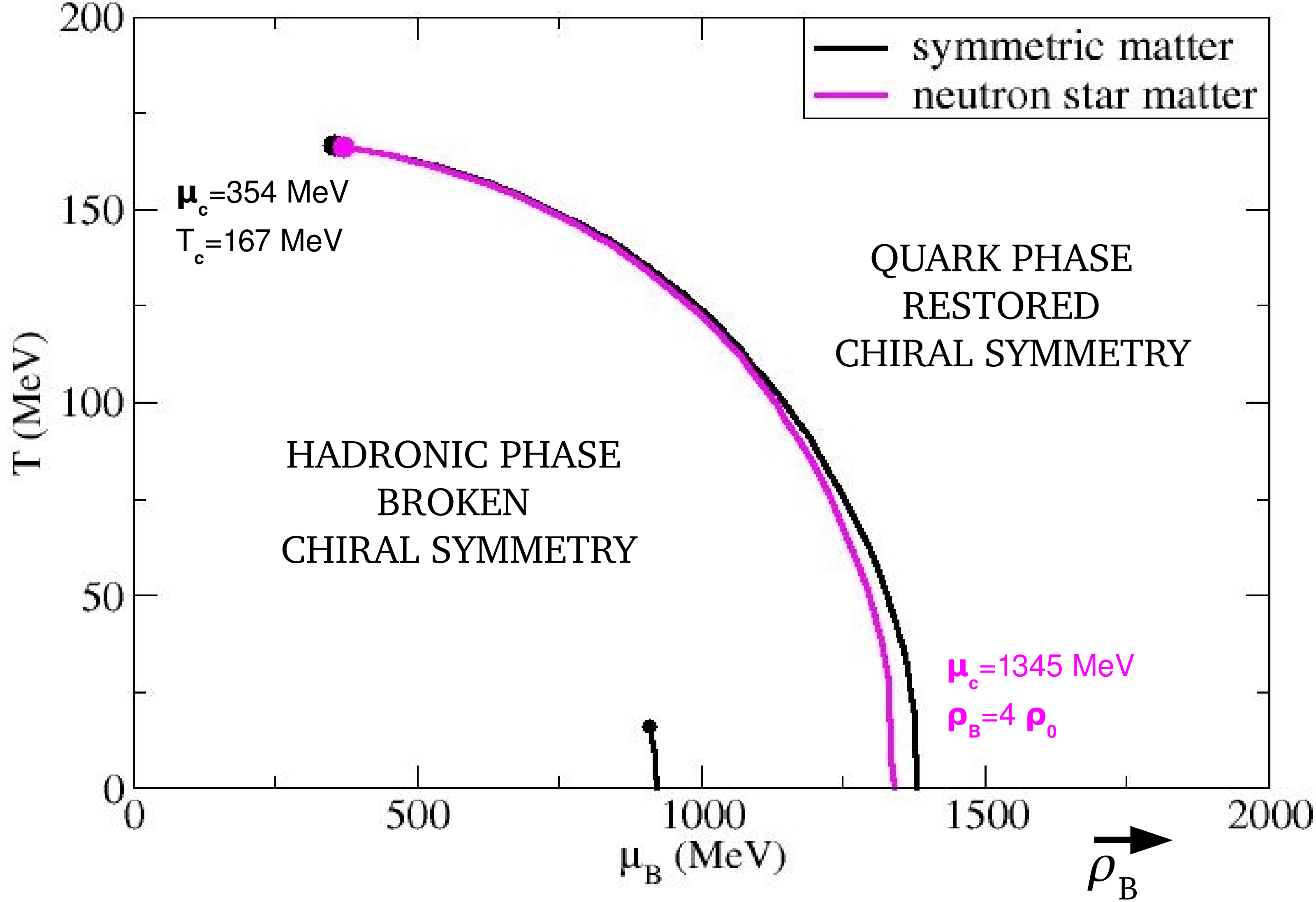



- Introduce a potential for $\Phi$ at any density and temperature

$$U = (a_0\, T^4 + a_1\, \mu^4 + a_2\, T^2\mu^2)\phi^2$$

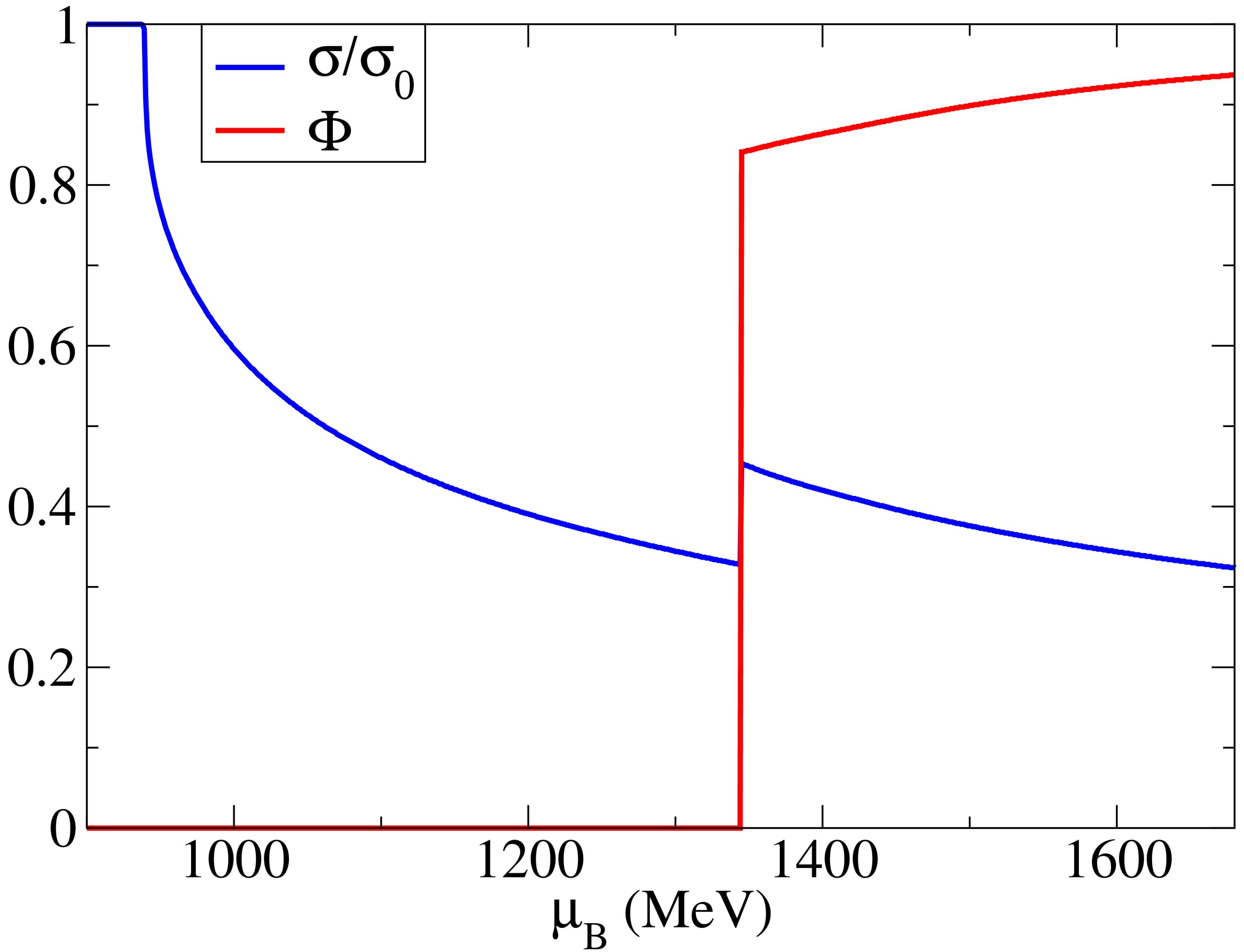
$$+\, a_3\, T_0^4 \quad \ln\left(1 - 6\phi^2 + 8\phi^3 - 3\phi^4\right)$$

# 6. Phase Diagram



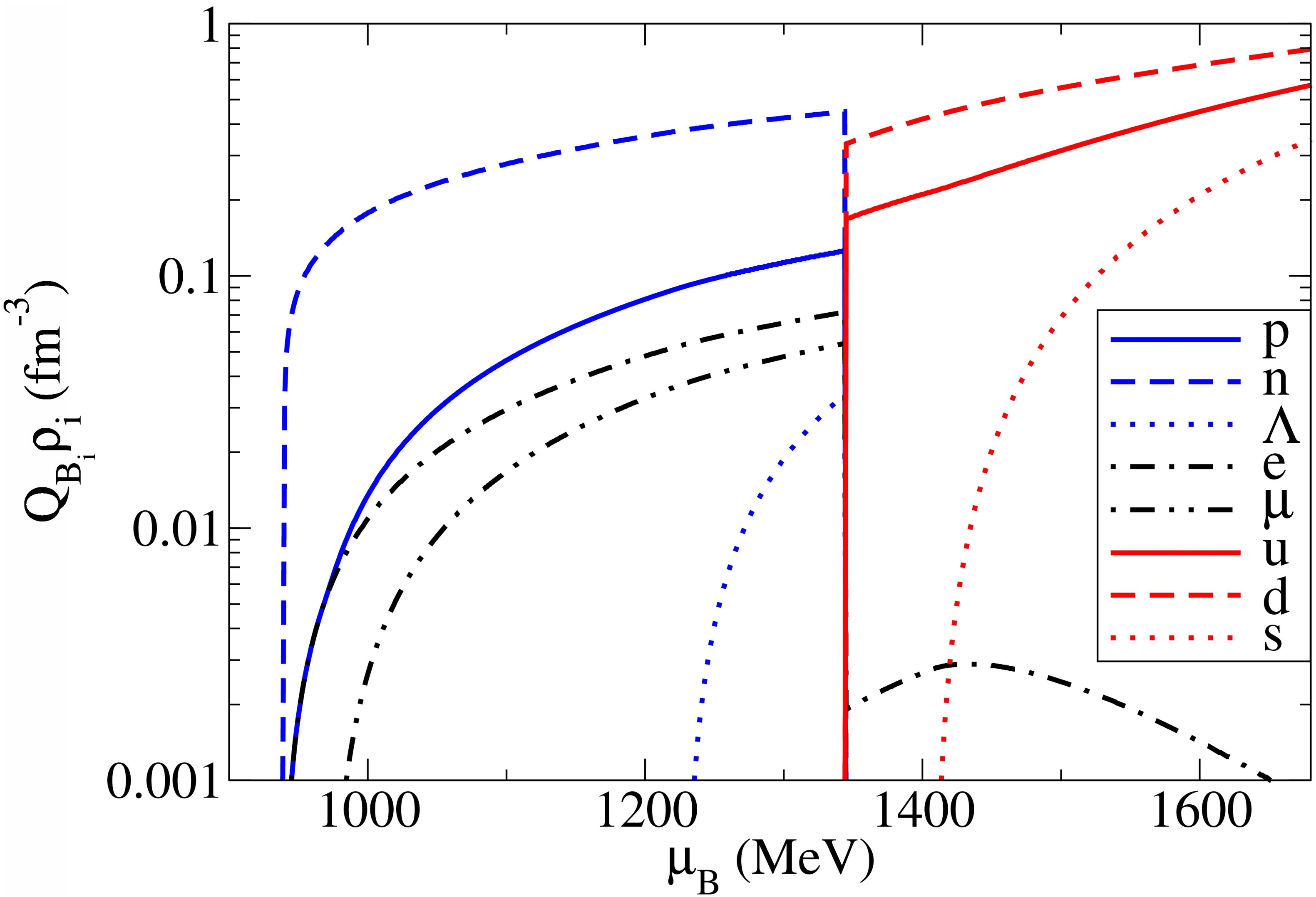

The first order phase transition line ends at a critical point.

# 7. Hybrid Stars (T=0)



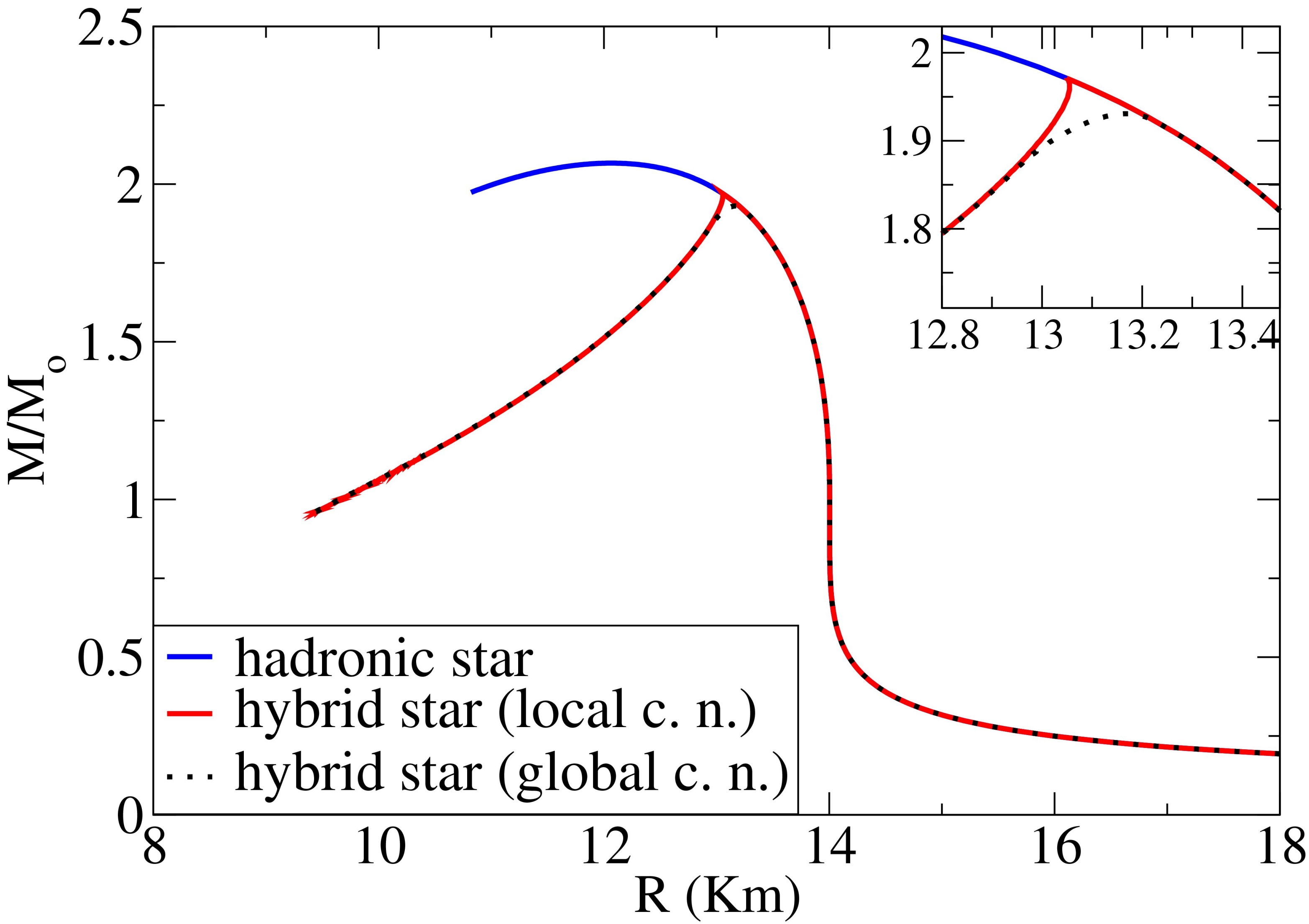

First order phase transition for *Φ* and the chiral condensate.

# Population (local charge neutrality)



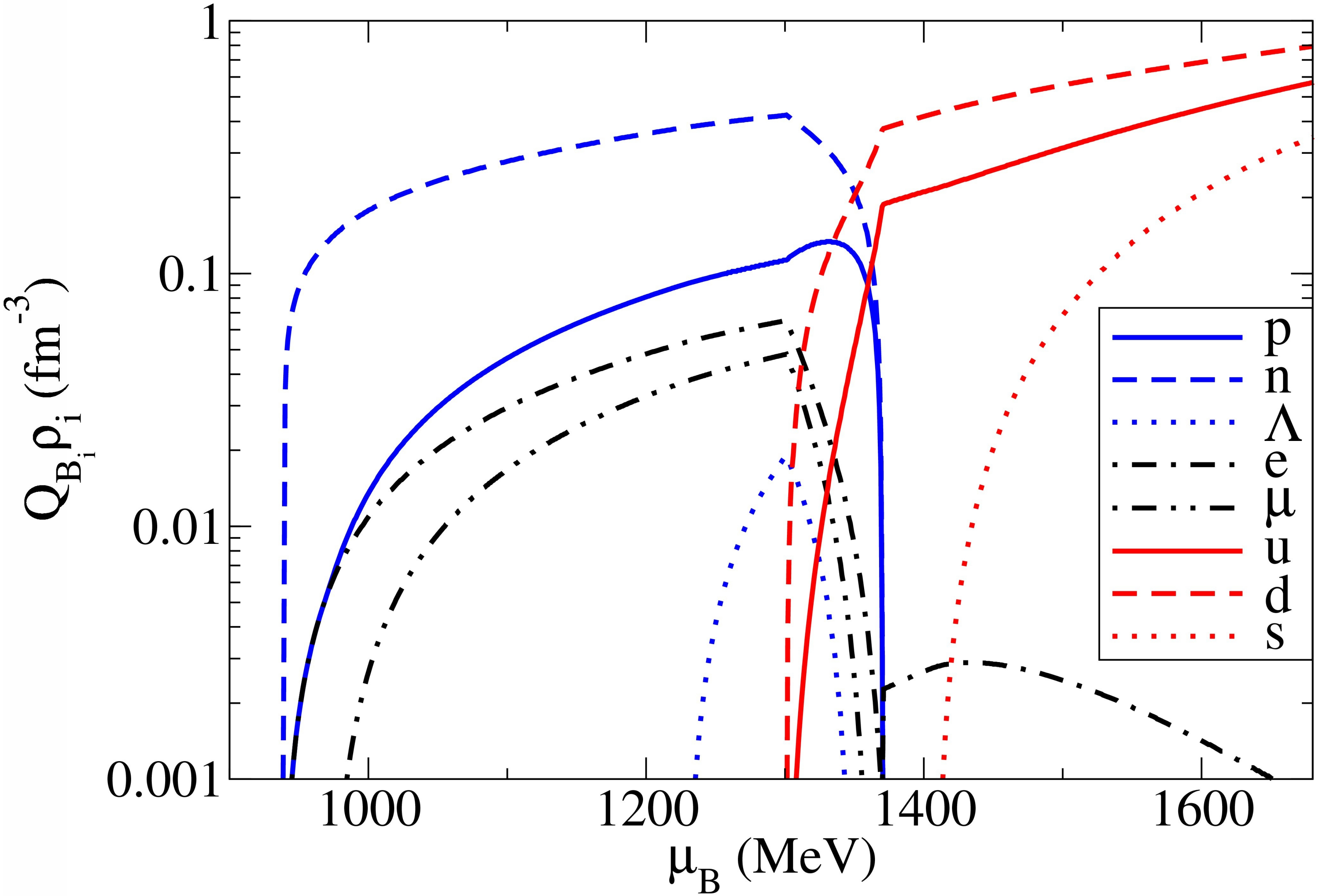

No mixed phase: just hadron matter or quark matter.

# 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.

# 8. Magnetic Field

- In the z direction and dependent on the chemical potential

$$B^* = B_{surf} + B_c[1 - e^{b_1(\frac{\mu_B - 939}{939})^{b_2}}]$$

69.25 MeV$^2$=10$^{15}$G

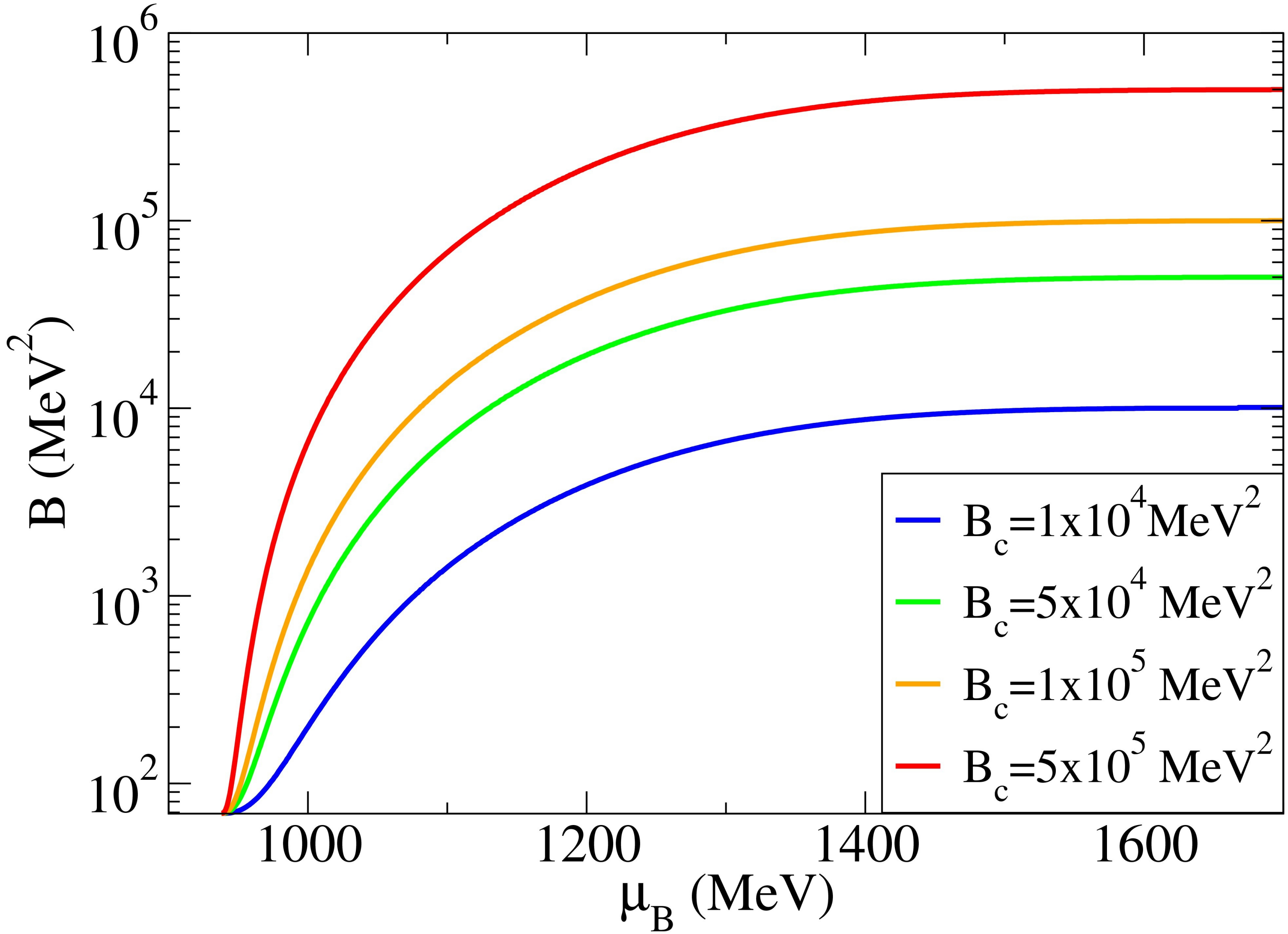
- Quantization of the energy levels in the x and y directions for the charged fermions

$$E_\nu = \sqrt{k_z^2 + m_i^{*2} + 2\nu|q|B}$$

until

$$\nu_{max} = \frac{E_F^{*2} - m_i^{*2}}{2|q|B}$$

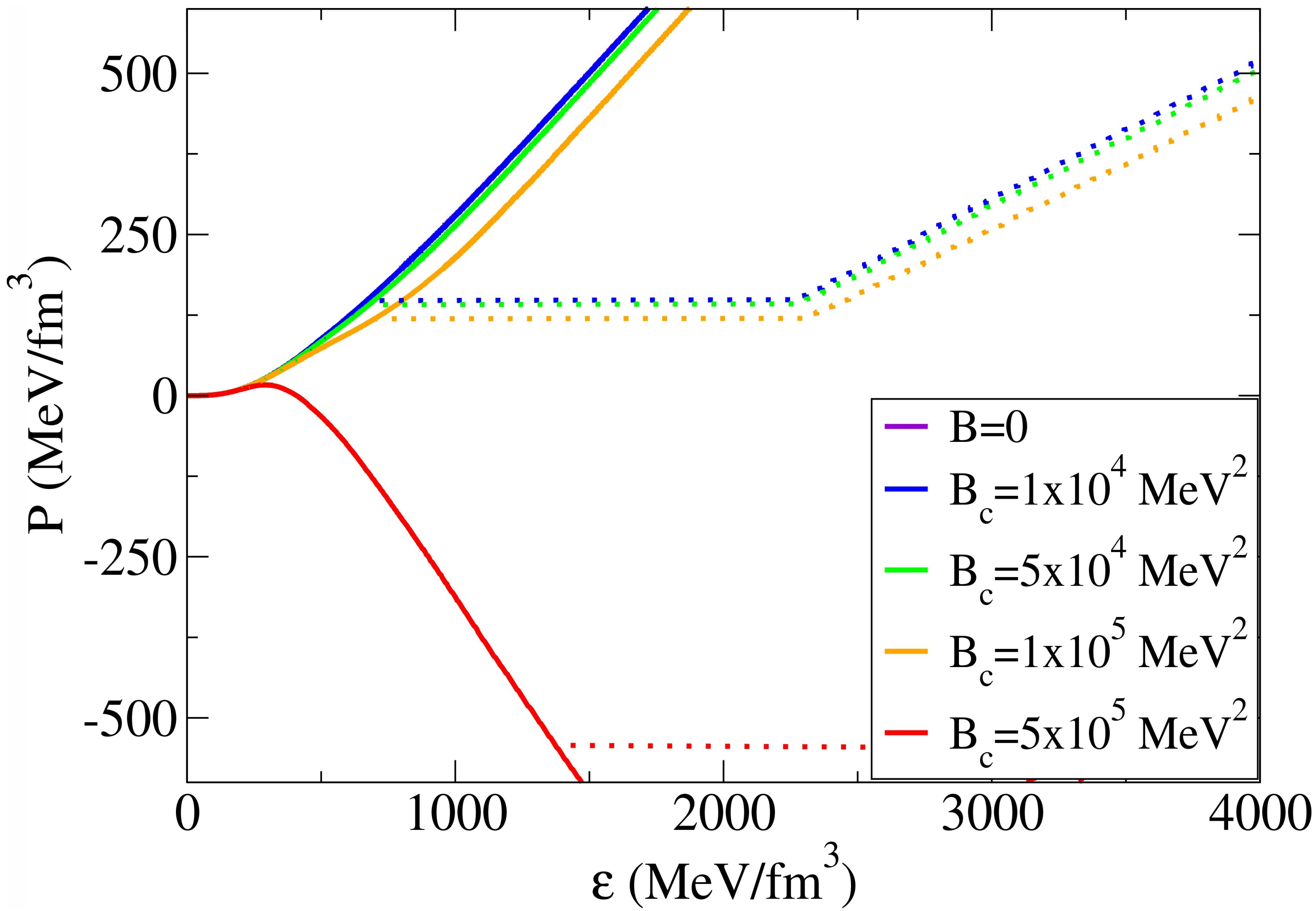
# Effective Magnetic Field




B increases toward the center of the star.

1MeV$^2$ = 1.444 x $10^{13}$ G

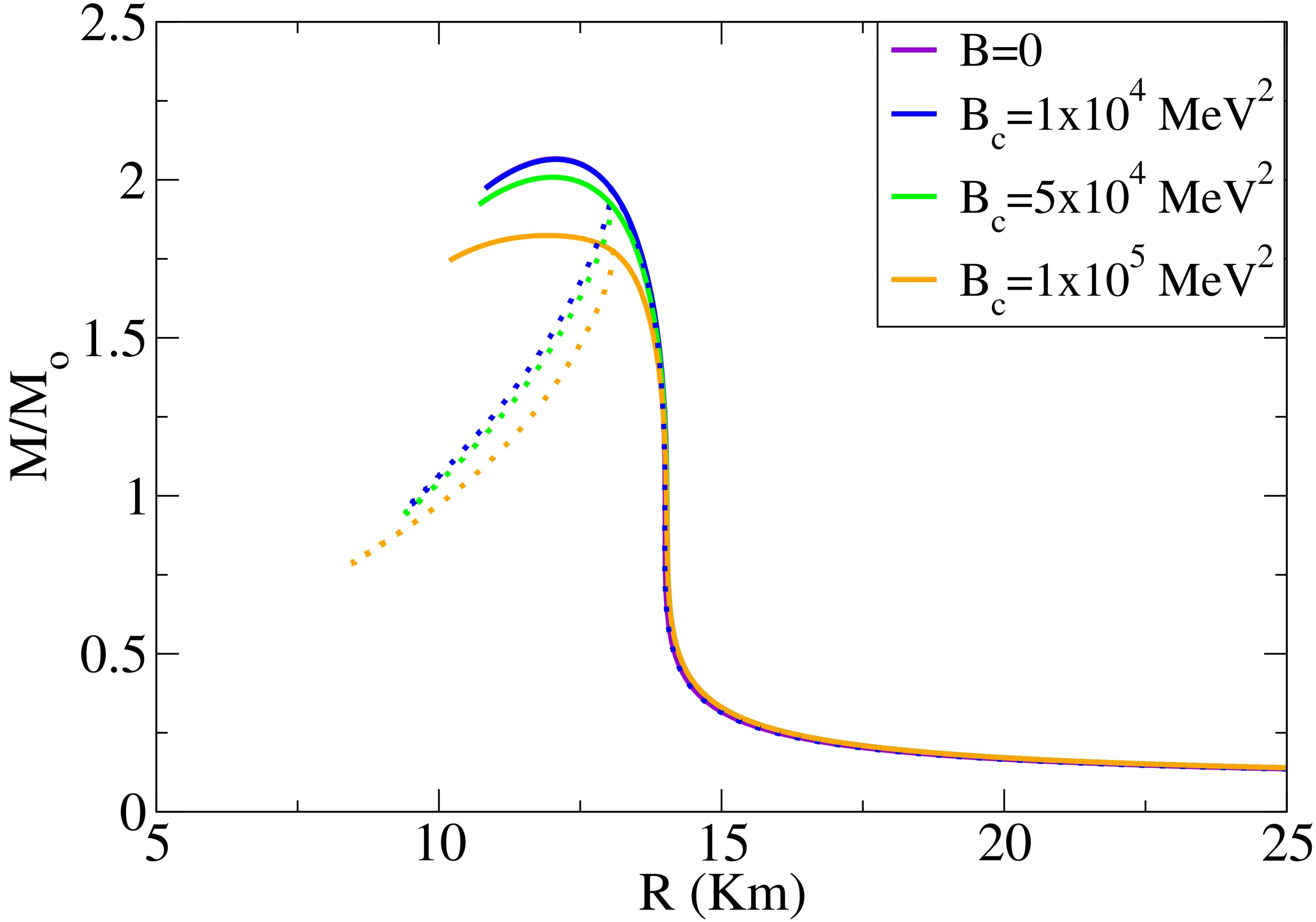
# Equation of State




EOS becomes softer and eventually unphysical with the increase of B.

$1 MeV^2 = 1.444 \times 10^{13}$ G

# Mass-Radius Diagram




Stars become less massive with the increase of B.

$1 MeV^2 = 1.444 \times 10^{13}$ G

# 9. Conclusions

- ✯ We can evaluate how chiral symmetry is restored and how deconfinement occurs since the degrees of freedom change naturally in our model from hadrons ↔ quarks

- ✯ We reproduce the physics of the entire phase diagram including lattice QCD, heavy ion collisions, nuclear physics and neutron star results

- ✯ For zero temperature (with global charge neutrality) we reproduce a mixed phase that allows stable (massive) star configurations with presence of hybrid matter up to 2 km

- ✯ The pressure behaviour establishes a limit for the magnetic field

- ✯ The presence of strong magnetic field allows deconfinement to happen at smaller chemical potential but reduces the mass of the respective star

# Outlook

- Apply the model to supernova matter to analyse how neutrino trapping affects the results
- Analyse the effect of magnetic field in the phase diagram:
  - proto-neutron stars
  - heavy ion collisions