A Self-consistent Study of Magnetic Field Effects on Hybrid Stars

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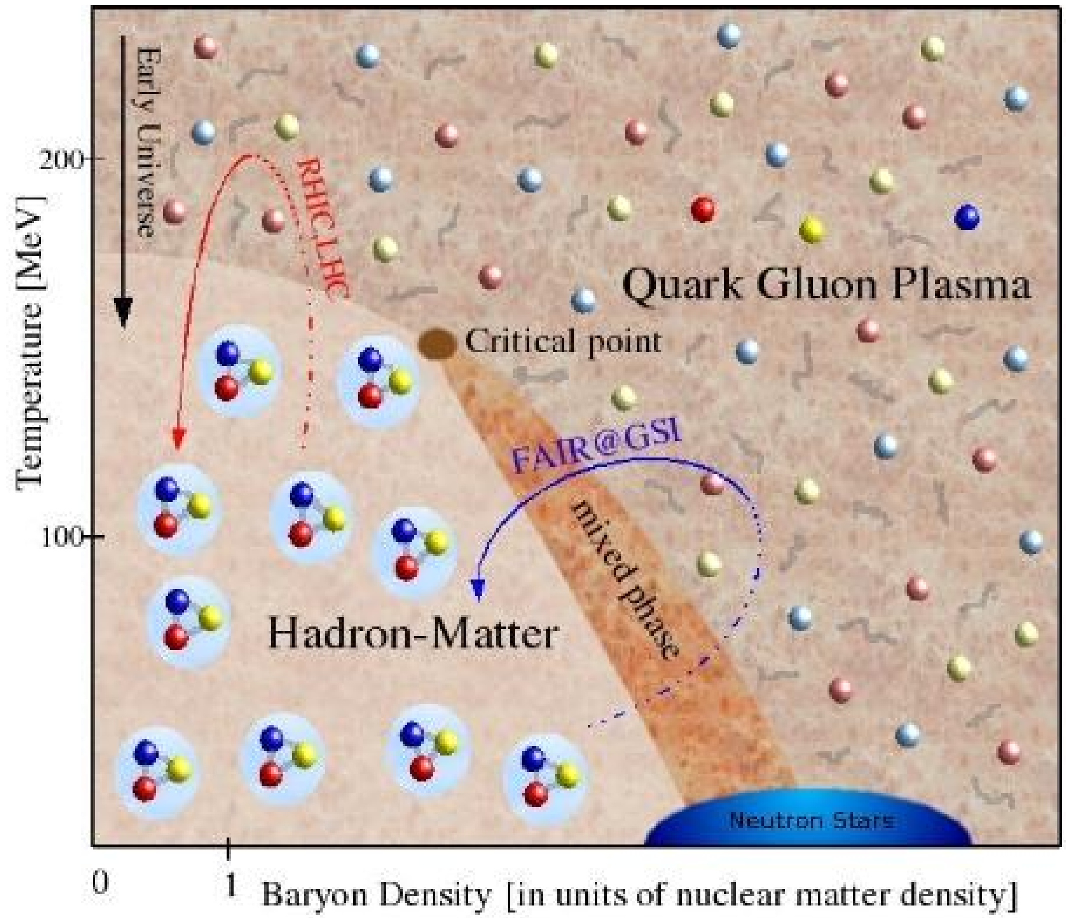
✯ Motivation

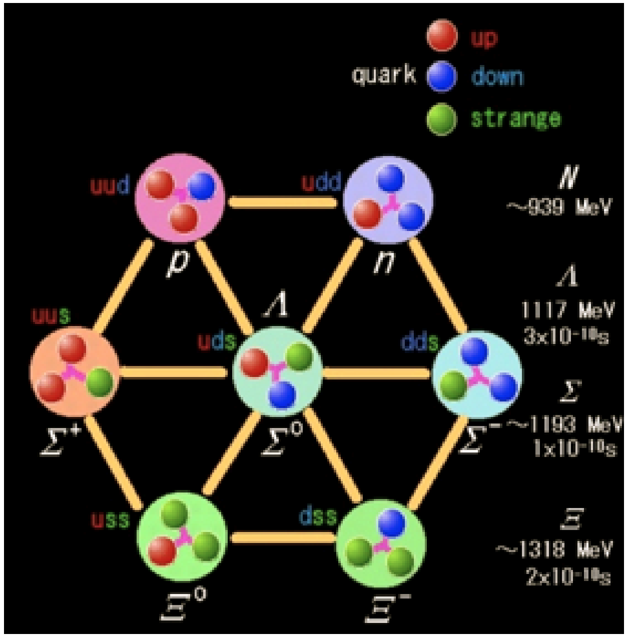
- understand neutron stars and low temperature /high density region of QCD phase diagram

- study effects on the EOS from:

• hyperonic degrees of freedom
• deconfinement to quark matter
• chiral symmetry restoration
• isospin asymmetry / charge neutrality
• strong magnetic fields / spin polarization



✭ Ingredients for EOS



- baryon octet: p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^-

- up, down, strange quark

- nuclear physics constraints:

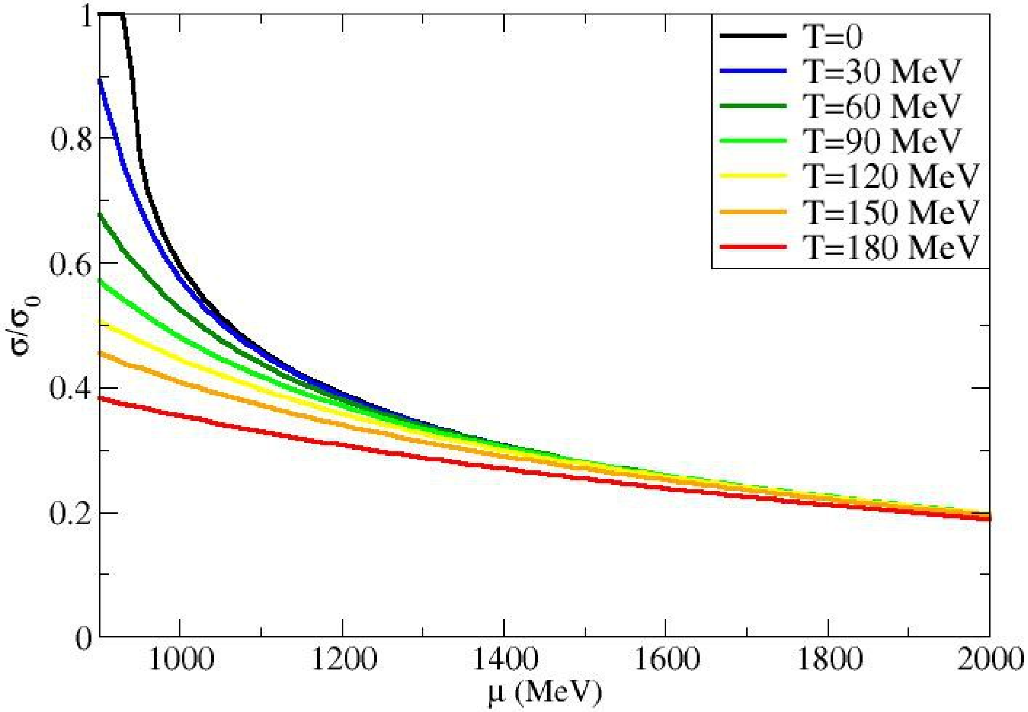
- vacuum masses of baryons and mesons
- pion and kaon decay constants
- saturation density (ρ_0=0.15 fm^{-3})
- binding energy at saturation (B=-16.00 MeV)
- nucleon effective mass at saturation (M^*_N=0.67 M_N)
- compressibility at saturation (K=297.32 MeV)
- symmetry energy at saturation (E_{sym}=32.50 MeV)
- hyperon potentials at saturation (U_Λ=-28 MeV, U_Σ=5.35 MeV, U_Ξ=-18.36 MeV)

⭑ Non-Linear Realization of the SU(3) Sigma Model

- effective quantum relativistic model → mean field

- describes hadrons interacting via meson exchange ($\sigma,\delta,\zeta,\omega,\rho,\phi$)

- constructed from symmetry relations → allow it to be chirally invariant → masses from interaction with medium



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

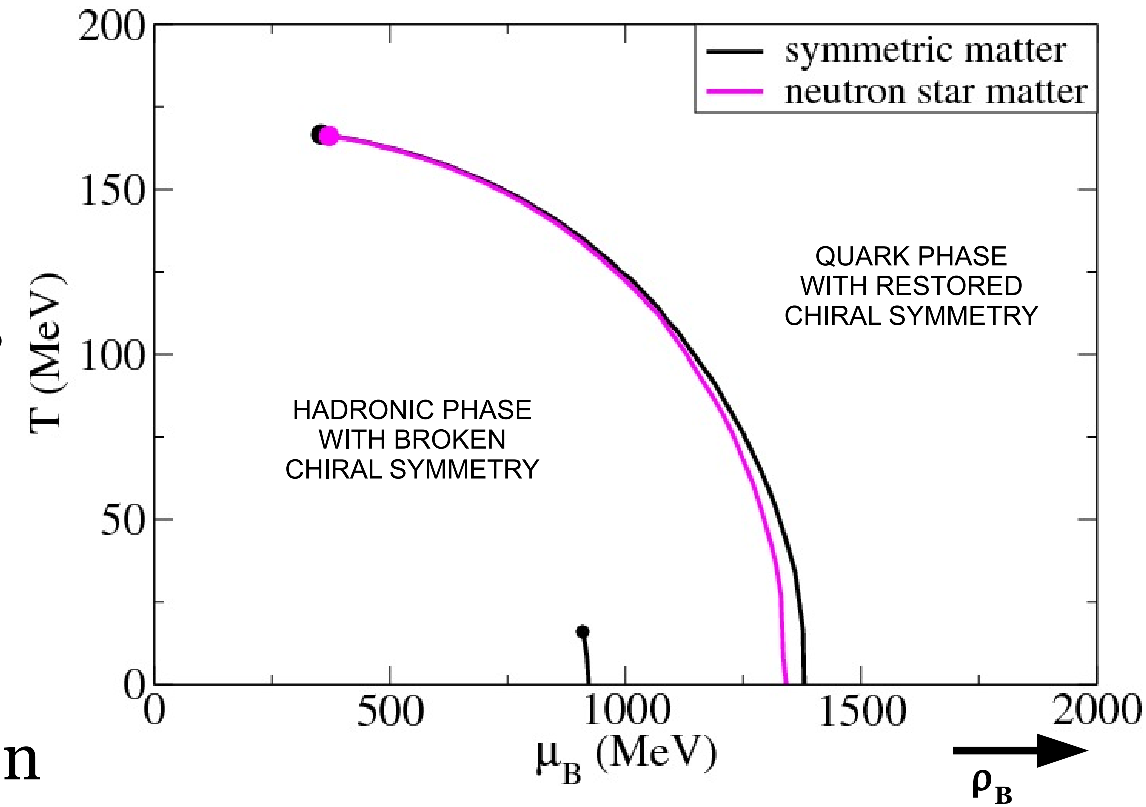
$$\delta m_b = 150\,MeV / 376.58\,MeV$$

Dexheimer et al. Astrophys.J. 2008

✯ Deconfinement

Dexheimer et al. Phys. Rev. C 2010

- hadrons + quarks
- effective masses
- 1st order phase transitions or crossovers
- order parameters σ, Φ
- potential for Φ (deconfinement)
- liquid-gas phase transition

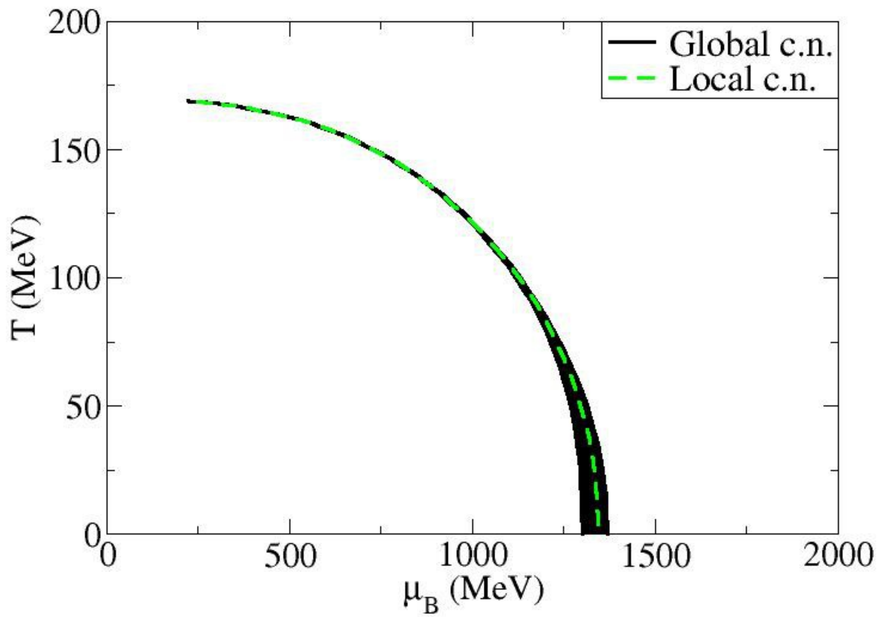


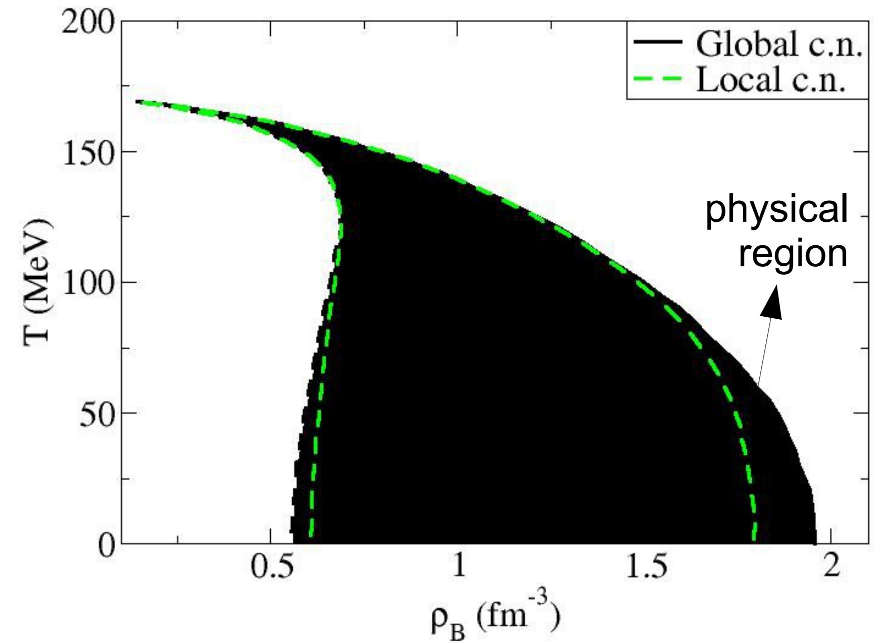
$$m_b^* = g_{b\sigma}\sigma + g_{b\delta}\tau_3\delta + g_{b\zeta}\zeta + \delta m_b + g_{b\Phi}\Phi^2$$
$$m_q^* = g_{q\sigma}\sigma + g_{q\delta}\tau_3\delta + g_{q\zeta}\zeta + \delta m_q + g_{q\Phi}(1-\Phi)$$

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

Local and Global Charge Neutrality

- absence / presence of mixture of phases (surface tension)





Hempel et al. Phys. Rev. C 2013

- different from liquid-gas:

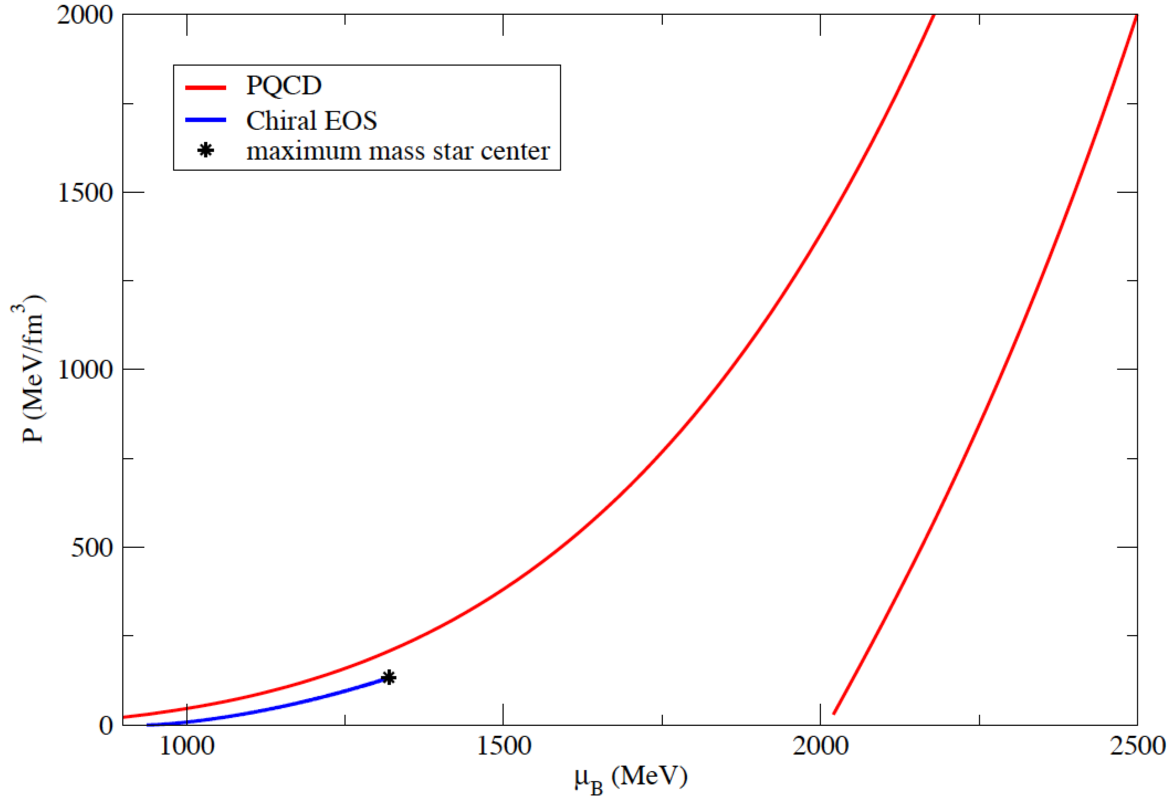
- same charged chemical potential in both phases
- local concentrations of a charge vary during phase transition
- non-congruent features (vanishingly small around critical point)
- negative slope in the pressure-temperature plane

✯ Perturbative QCD:

- comparison with PQCD data from: Fraga, Kurkela and Vuorinen, Astrophys. J. 2014

- 3-flavor QGP at zero temperature including β-equilibrium and charge neutrality

- band reflects uncertainties



✯ Magnetic Field in EOS at T=0

- B in the z-direction
- x, y energy levels quantized
- anomalous magnetic moment (AMM)

$$E^*_{i_{\nu s}} = \sqrt{k^2_{z_i} + \left(\sqrt{m_i^{*2} + 2\nu|q_i|B^*} - s_i\kappa_i B^*\right)^2}$$

$$E^*_{i_s} = \sqrt{k^2_i + \left(m_i^{*2} - s_i\kappa_i B^*\right)^2}$$

$\kappa_i \rightarrow$ coupling strength of baryons with electromagnetic field tensor

maximum Landau level

$$\nu_{max} = \frac{E^{*\,2}_{i_s} + s_i\kappa_i B^* - m_i^{*2}}{2|q_i|B^*}$$

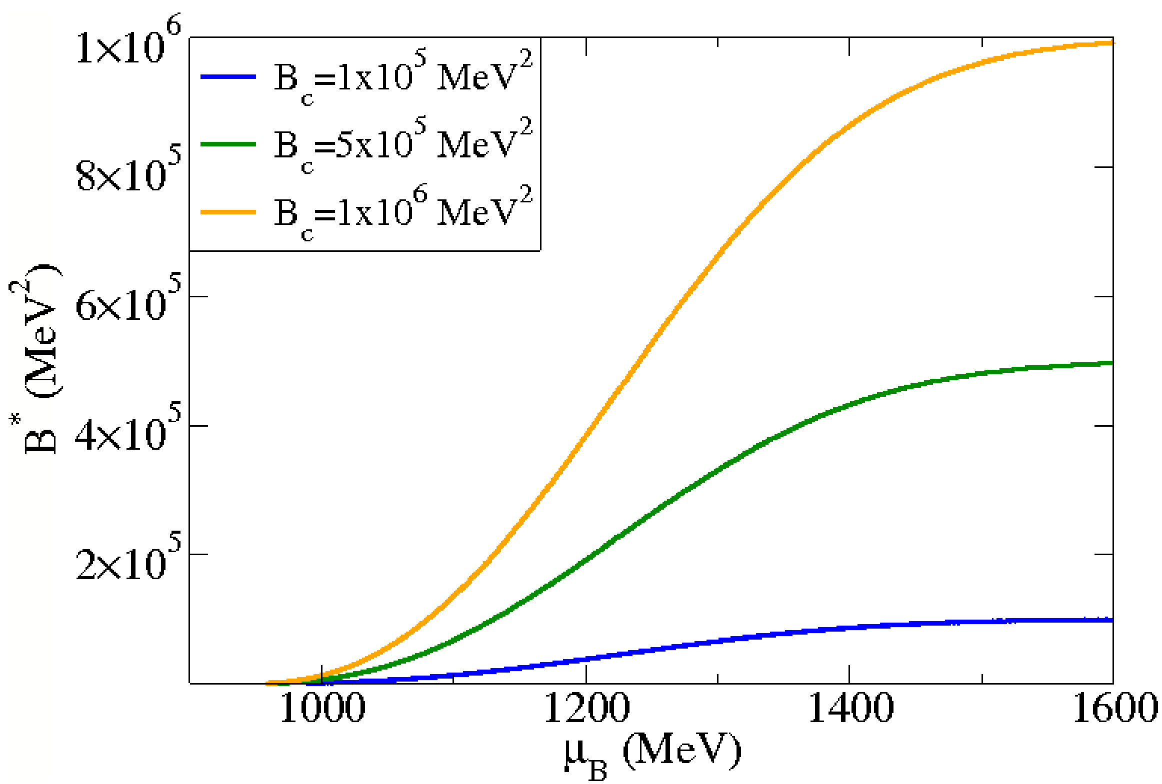
✯ Medium-dependent B

- B in the z-direction
  but dependent on μ_B

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

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

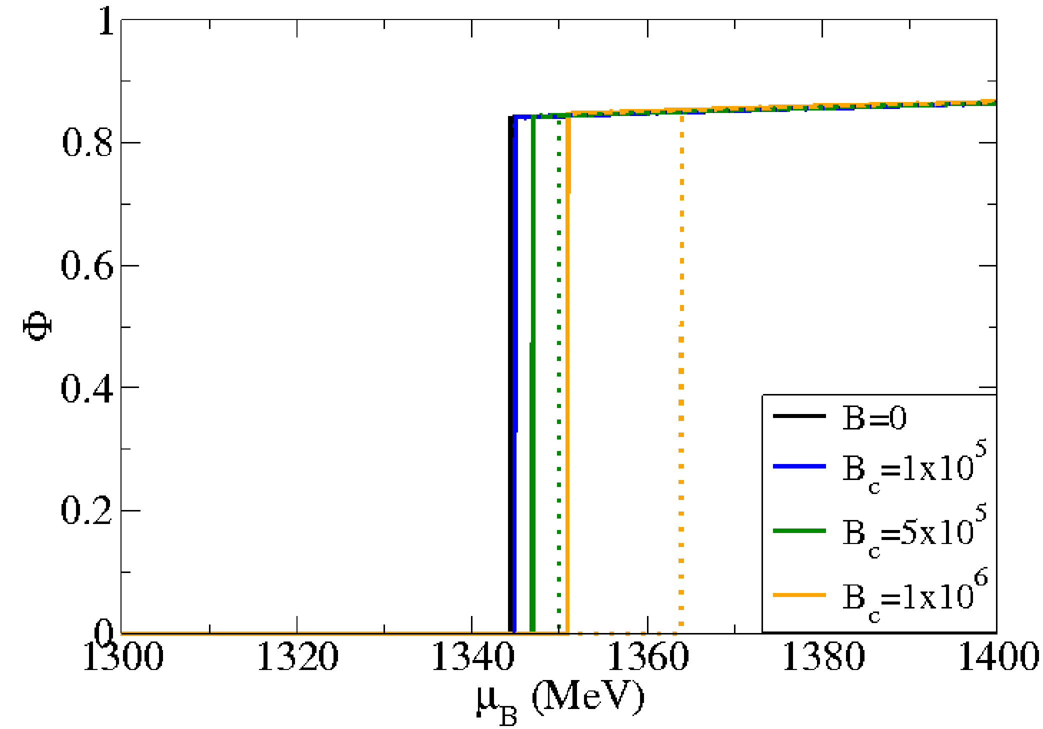
Dexheimer et al. Eur. Phys. J. 2012



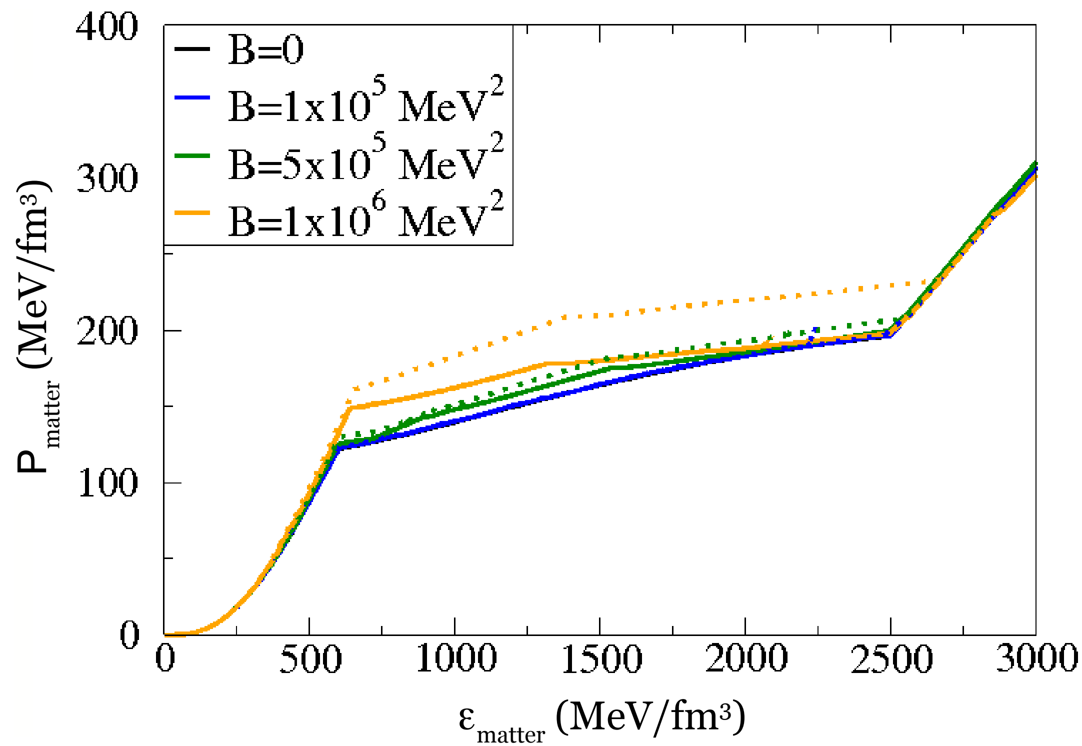
1 MeV ^{2} = 1.444 x 10^{13} G

✯ Phase Transition

- B delays deconfinement (associated with chiral symmetry restoration)
- effect increased by AMM (dotted line)



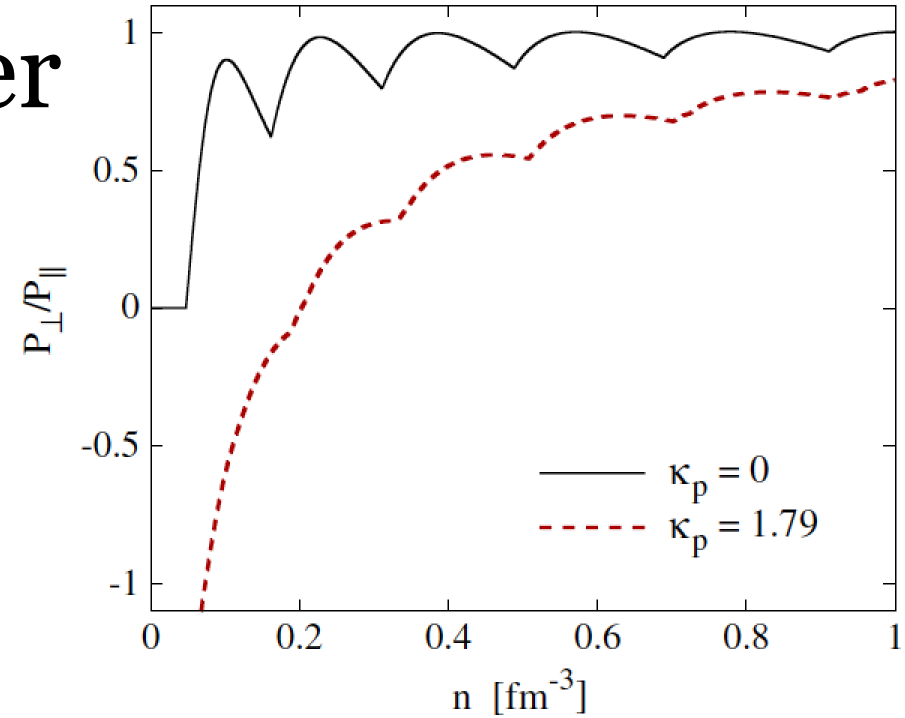
- equation of state gets stiffer with B
- enough to change mass?
- cannot use TOV !!!



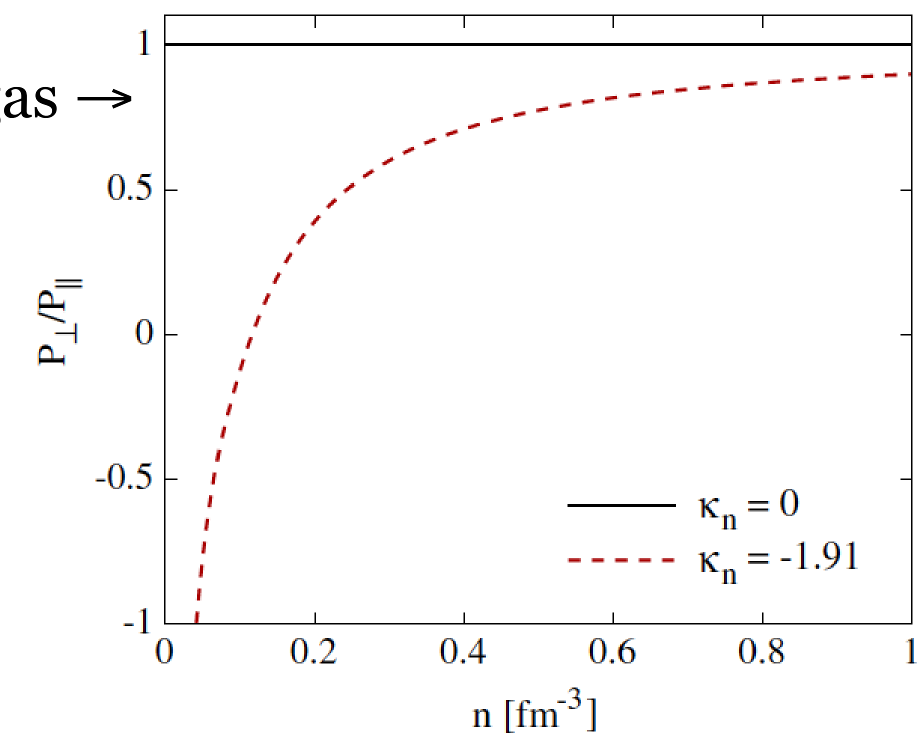
✭ Asymmetry in Matter

- pressure asymmetry on matter due to magnetization $P_{\perp\ \text{matter}} = P_{\text{matter}} - MB$ with $M = -\partial\Omega/\partial B$

- effects without/with AMM on proton gas →



- effects with AMM on neutron gas →



- matter pressure asymmetry decreases with temperature

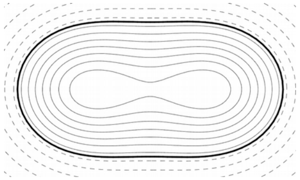
Strickland et al. Phys. Rev. D 2012

Maxwell-Einstein Equations (Lorene)

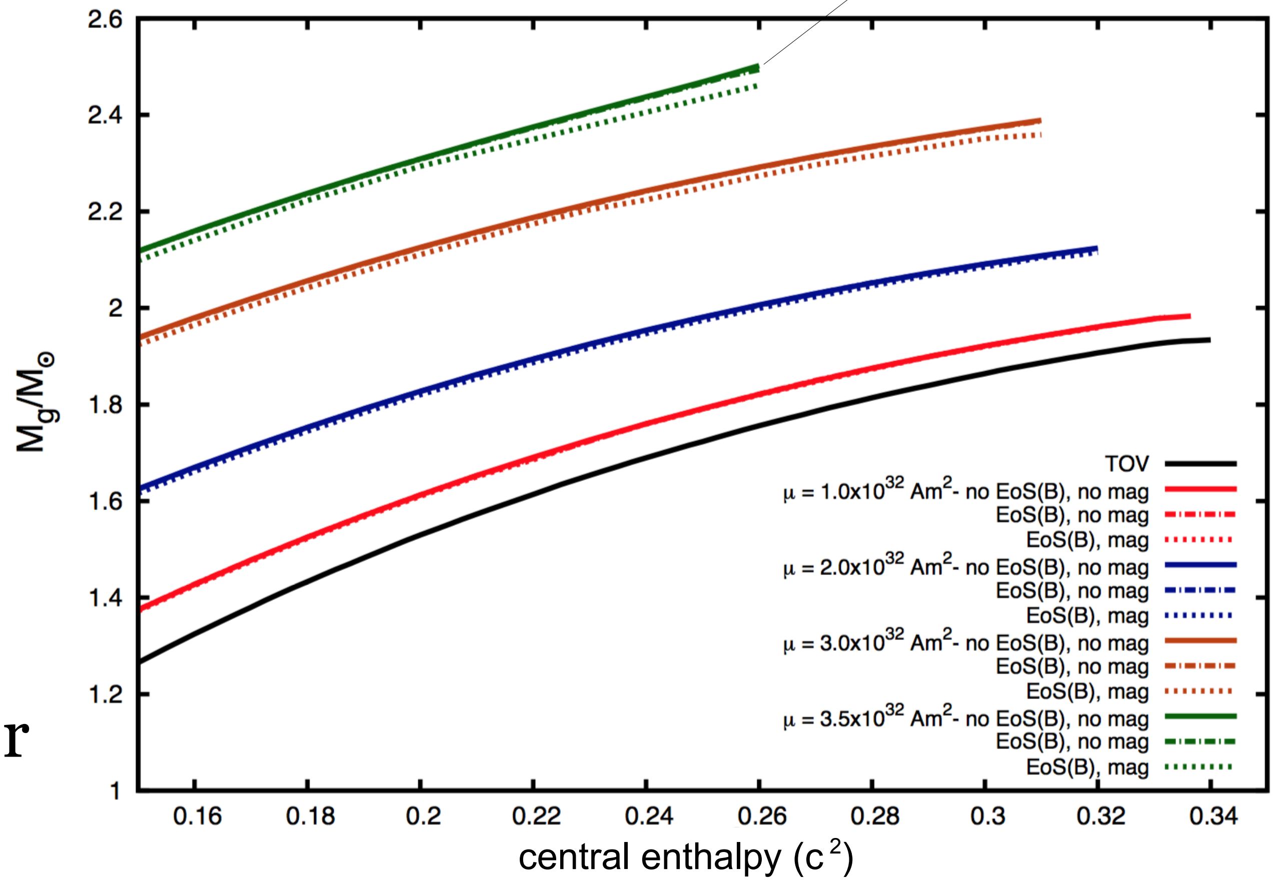
- axisymmetric poloidal magnetic field

Bonazzola et al. Astron. Astrophys. 1993

$r_p/r_{eq} \sim 0.5$



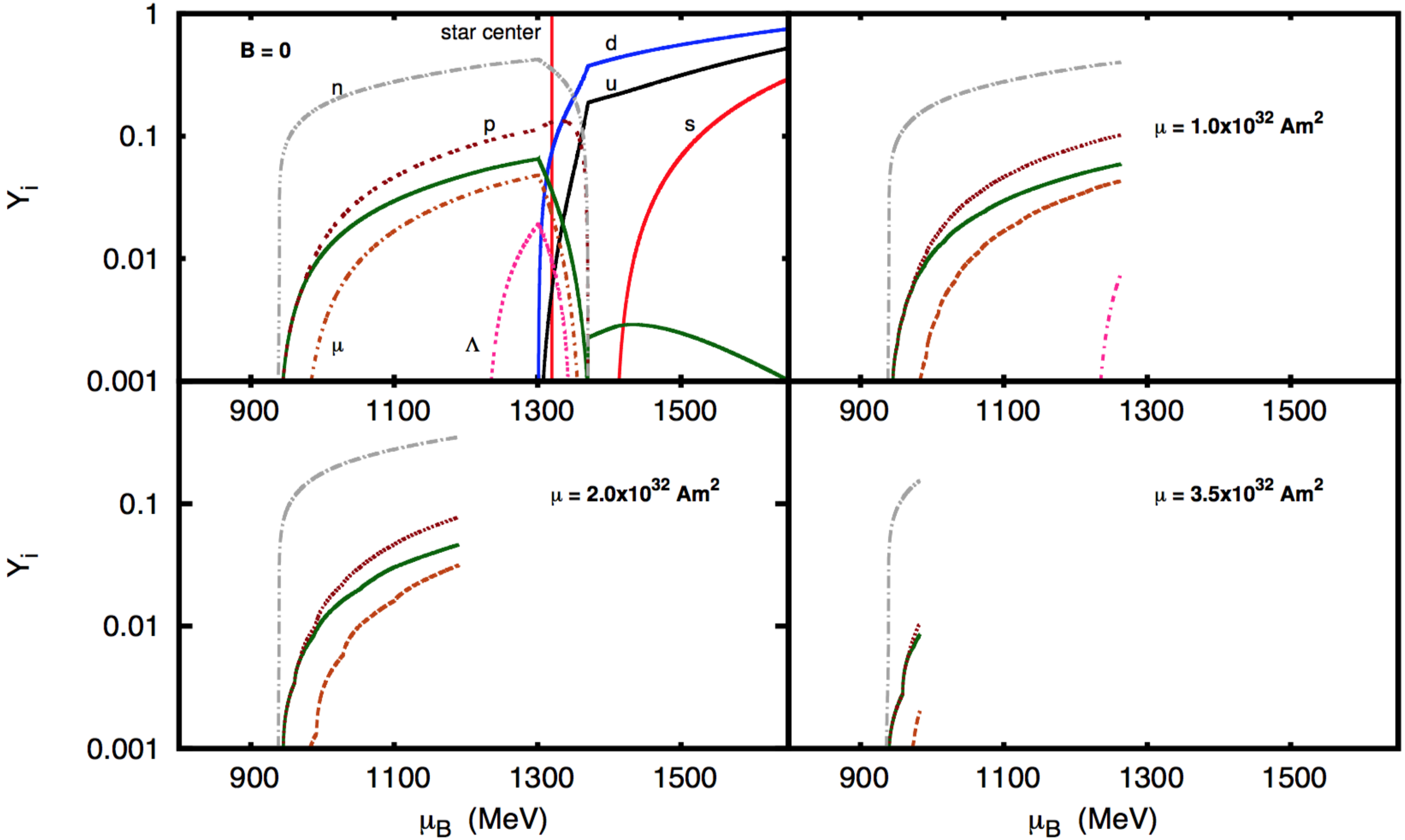
- anisotropic energy-momentum tensor due to:
  - pure B contribution
  - B in EOS (AMM)
  - magnetization
- B in EOS determined self-consistently for different magnetic dipole moments μ



Franzon et al. Mon. Not. Roy. Astron. Soc. 2016

✯ Population

- different compositions for different magnetic dipole moments μ (magnetic field distributions) at fixed baryon mass
- magnetic field decay accompanied by deconfinement?



Summary and Outlook

- strong magnetic fields do modify star properties but we cannot use TOV to investigate them!
- magnetic fields modify the structure and population of stars
- population needs to be calculated including magnetic field effects in the EOS
- a complete EOS must include hyperons and quarks
- we are currently including temperature effects in our magnetized EOS