Deconfinement Phase Transition in Hot and Dense Matter

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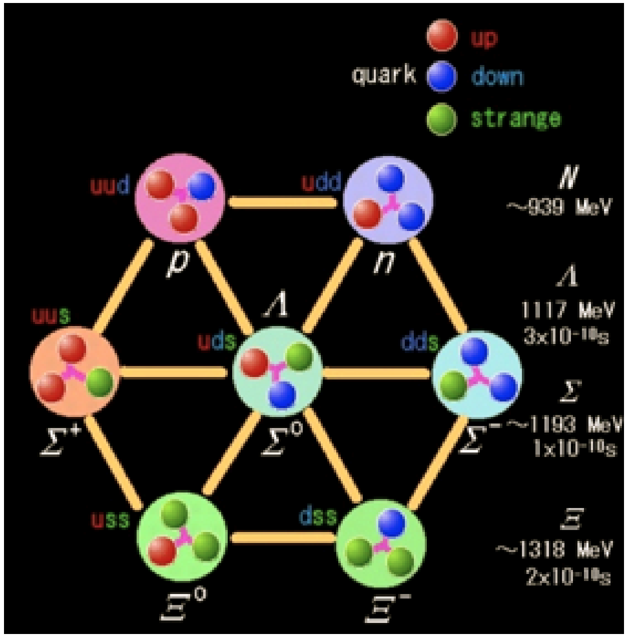
⋆ Ingredients of Description:

- baryon octet: p, n, Λ, Σ^+, Σ^o, Σ^-, Ξ^o, Ξ^-
- up, down, strange quark



- nuclear physics constraints:
  - vacuum masses of baryons and mesons
  - pion and kaon decay constants
  - saturation density (ρ_o=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 SU(3) Sigma Model:

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

- σ signals chiral symmetry restoration

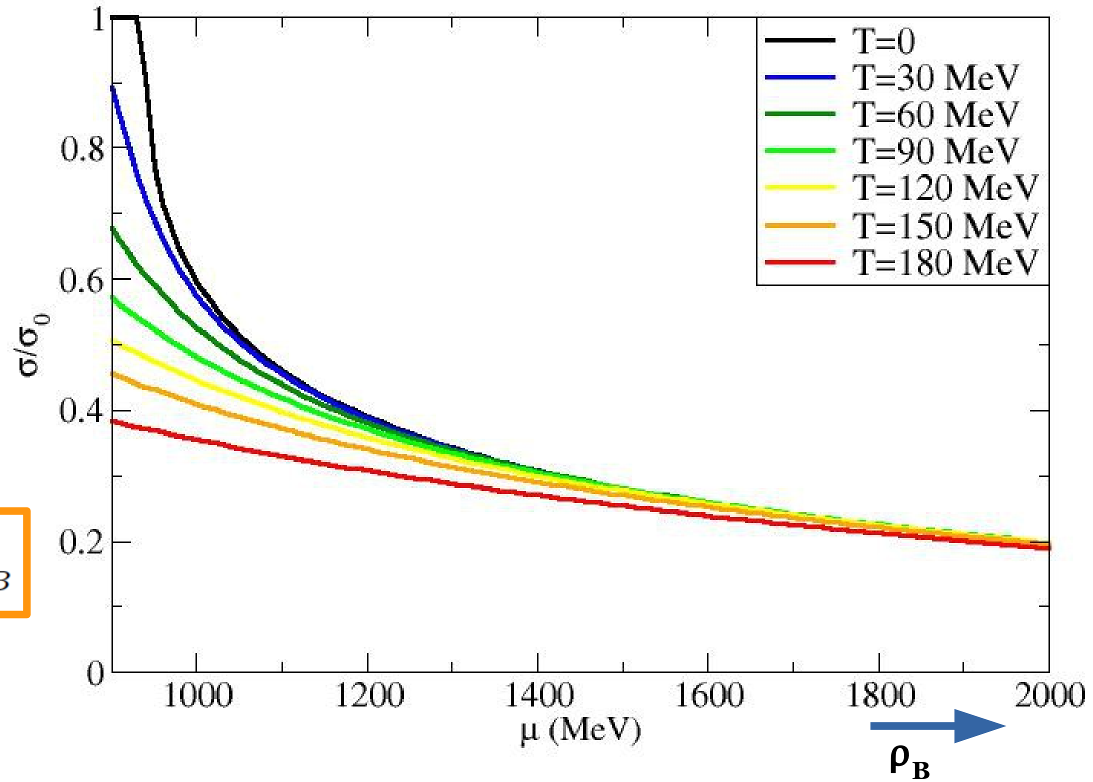
- pseudo-scalar mesons as parameters of chiral transformation

- describes hadrons interacting via meson exchange (σ, δ, ζ, ω, ρ, ϕ)

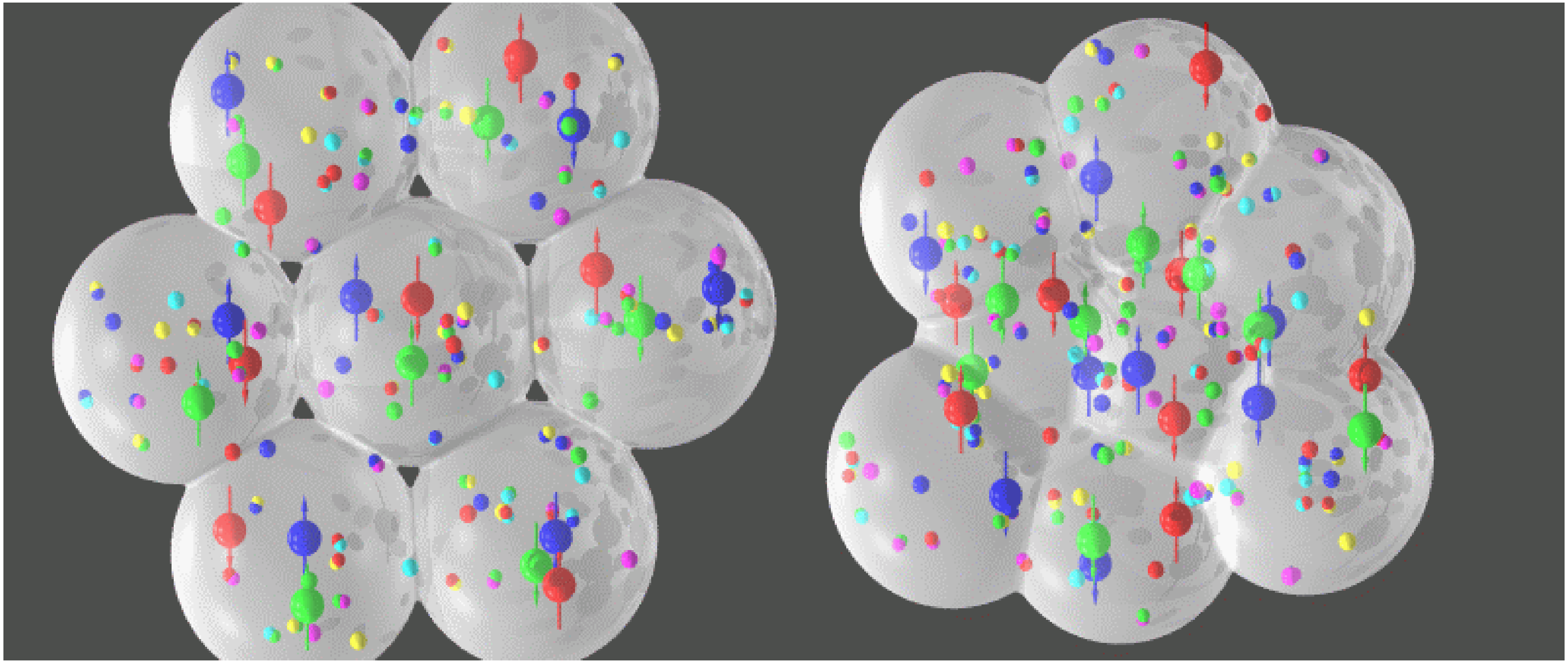
- MFT approximation

Dexheimer et al. Astrophys.J. 2008
Negreiros et al. Phys. Rev. C 2010

$$M_B^* = g_{B\sigma}\sigma + g_{B\delta}\tau_3\delta + g_{B\zeta}\zeta + m_{0_B}$$



✯ Deconfinement:

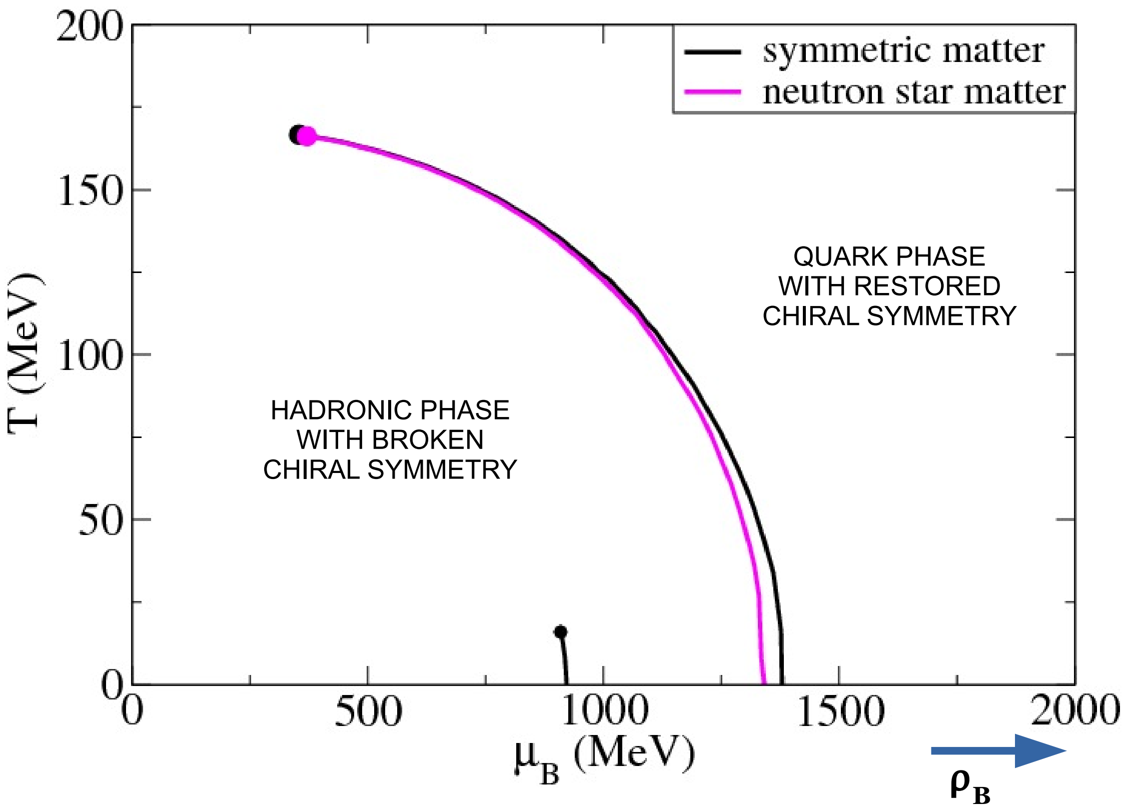


increase of density ρ_B

- new degrees of freedom: quarks: u, d, s

✯ Deconfinement in Model:

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



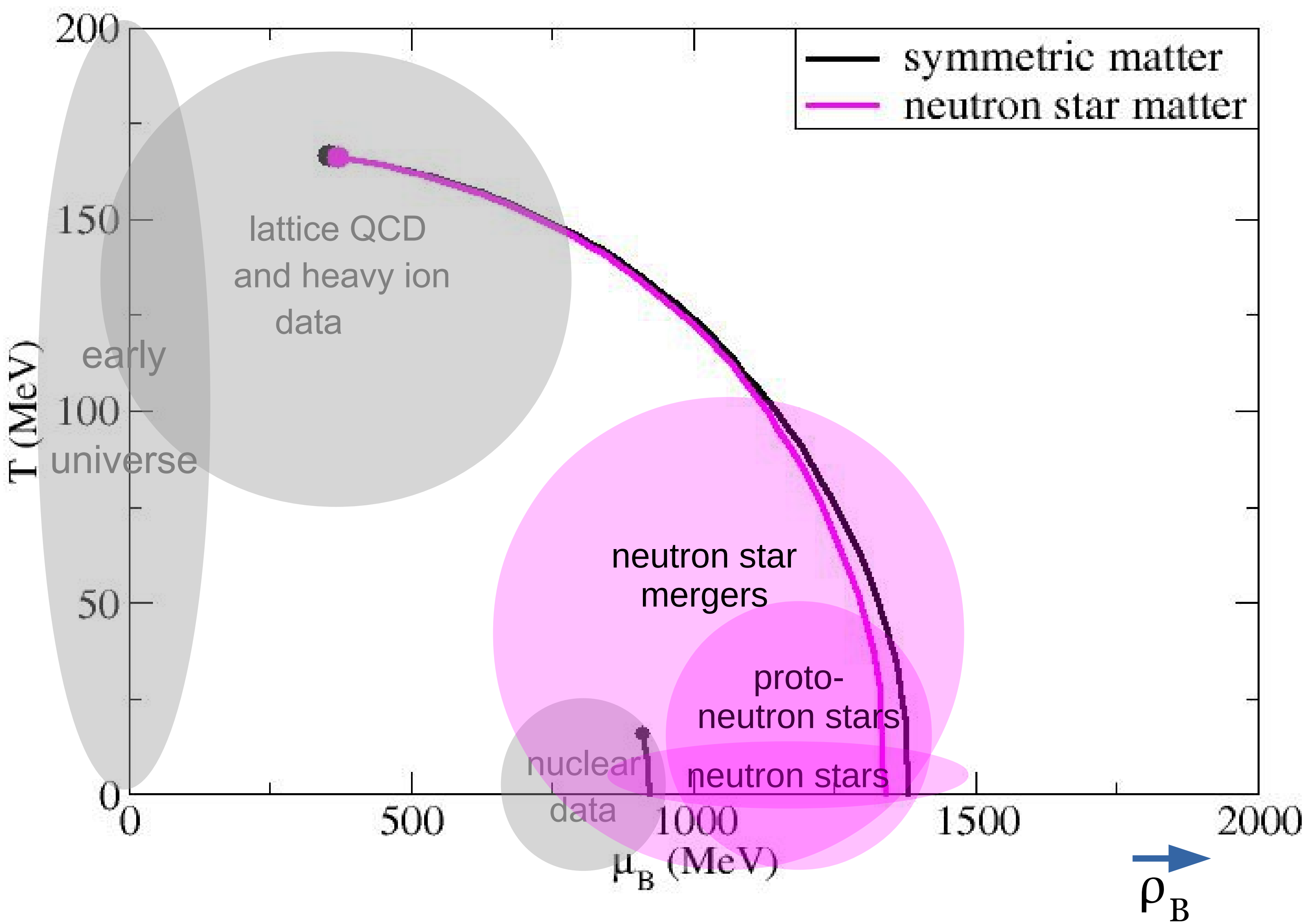
$$m_b^* = g_{b\sigma}\sigma + g_{b\delta}\tau_3\delta + g_{b\zeta}\zeta + \delta m_b + g_{b\Phi}\Phi^2$$

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

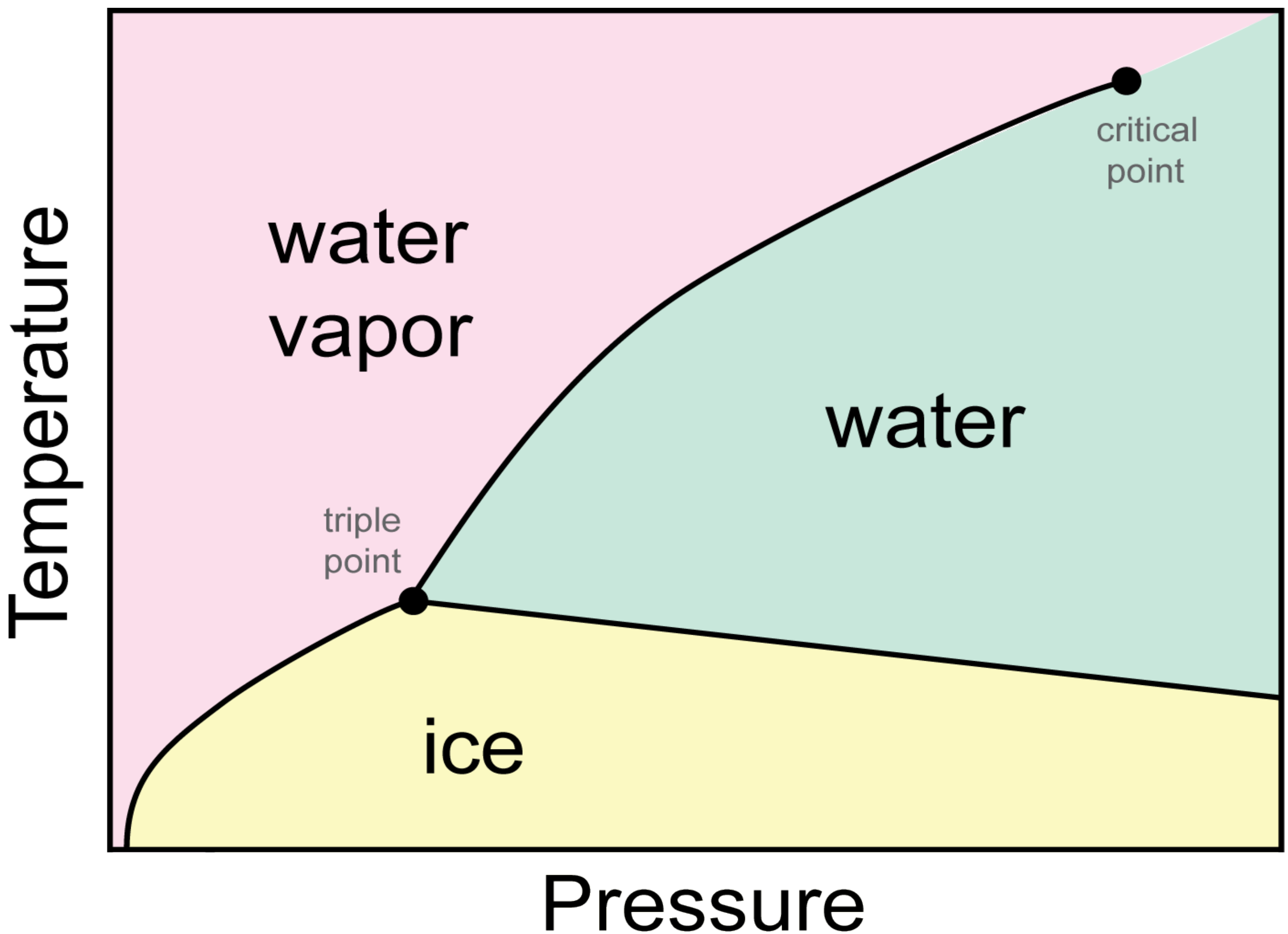
$$U = (a_0\, T^4 + a_1\, \mu^4 + a_2\, T^2\mu^2)\phi^2 + a_3\, T_0^4 \quad \ln\left(1 - 6\phi^2 + 8\phi^3 - 3\phi^4\right)$$

✯ General Picture:

Dexheimer et al. Phys. Rev. C 2010

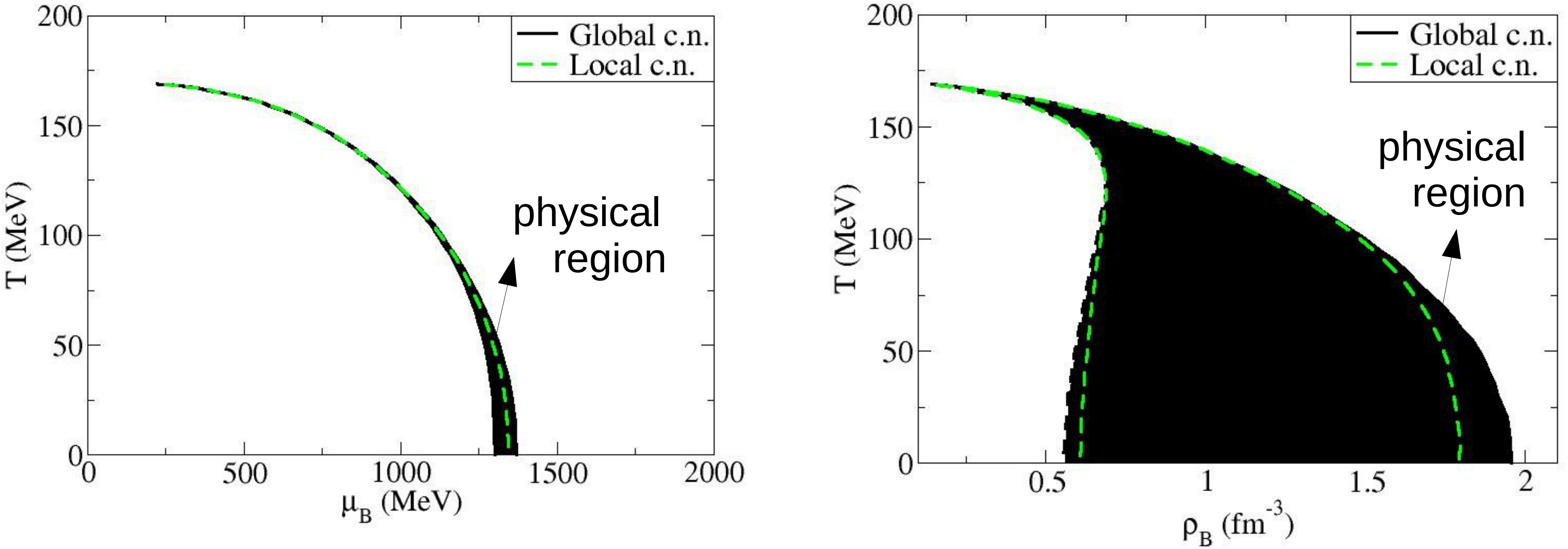


* Water Phase Diagram:



✯ Neutron Star Matter: Local and Global Charge Neutrality:

- absence / presence of mixture of phases: surface tension ???
- “mixed” quantities like $\rho_B = \lambda \rho_B^Q + (1-\lambda)\rho_B^H$



Hempel et al. Phys. Rev. C 2013

✯ Non-congruent Phase Transitions:

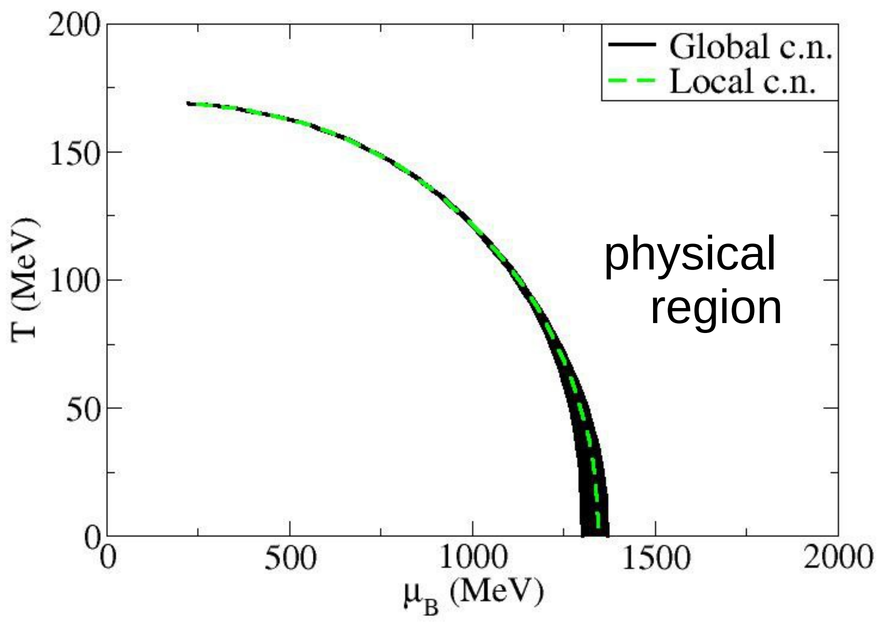
- more than one globally conserved charge within 2 macroscopic phases within a Coulomb-less model: baryon #, electric charge

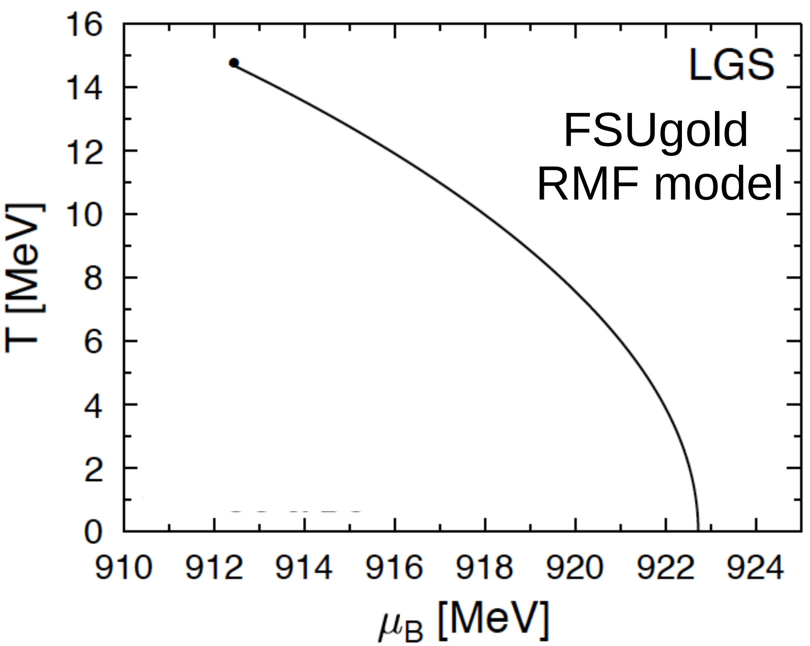
- local concentration of a charge varies during phase transition

- same chemical potential (assoc. to charge) in both phases (μ_q)

- but non-congruent features vanish around critical point

- different from symmetric matter liquid-gas





✭ More Comparison with Liquid-Gas:

Clausius-Clapeyron equation

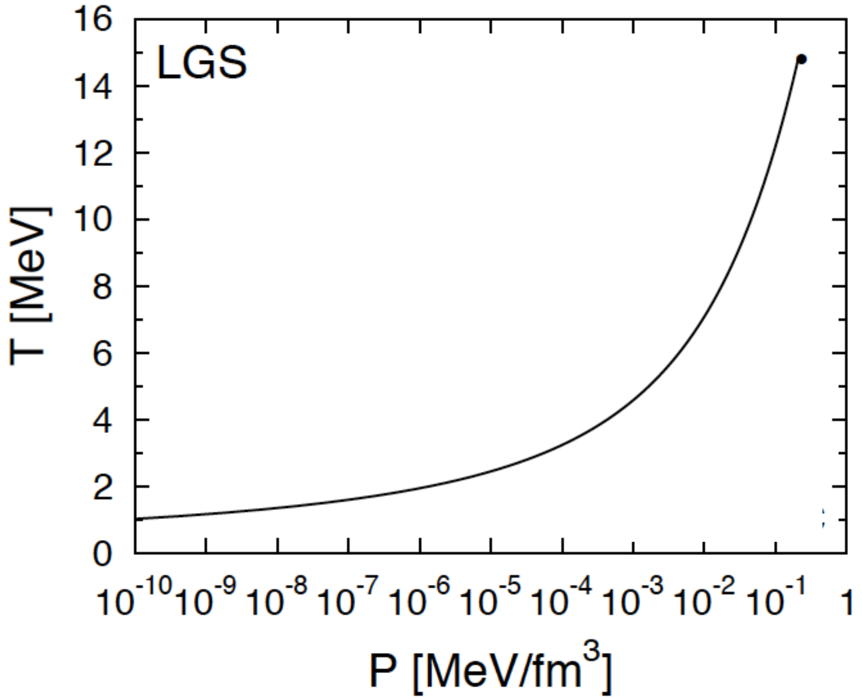
$$\frac{dP}{dT} = \frac{s^{I} - s^{II}}{1/\rho_B^{I} - 1/\rho_B^{II}}$$

- $s_q^{II} > s_h^{I}$, $\rho_{Bq}^{II} > \rho_{Bh}^{I}$

so dP/dT < 0 for deconfinement!

- $s_L^{II} < s_G^{I}$, $\rho_{BL}^{II} > \rho_{BG}^{I}$

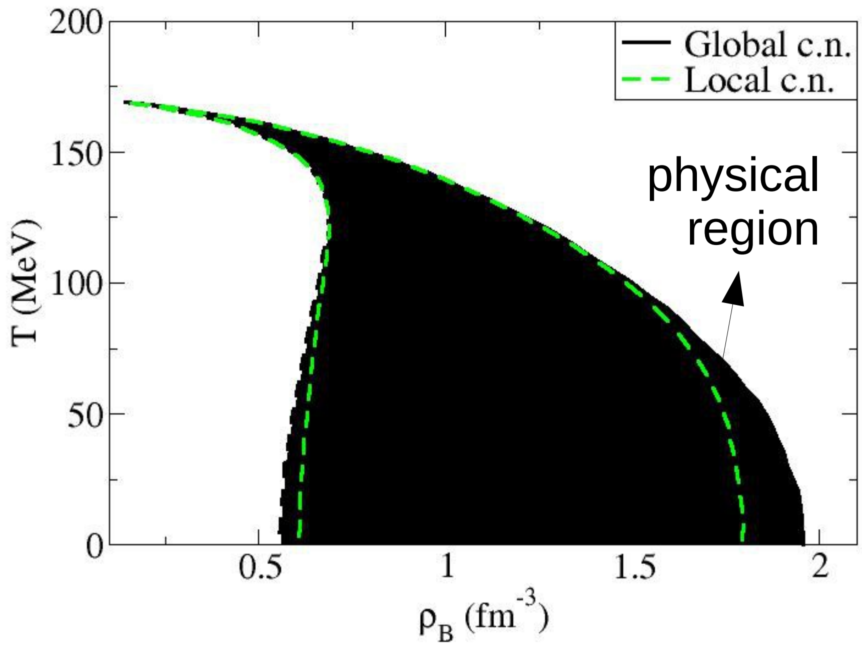
so dP/dT > 0 for L-G!

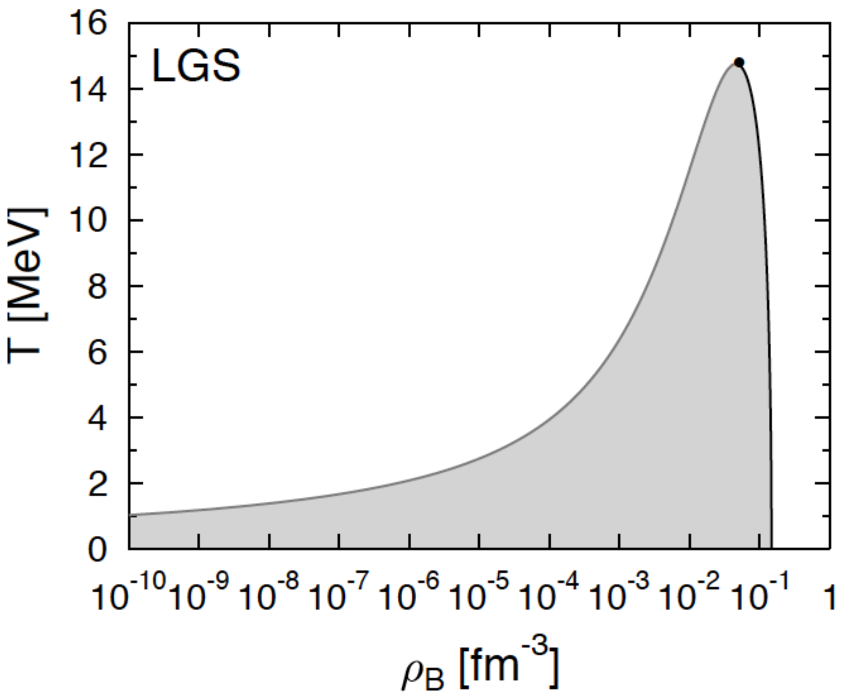


✯ More Comparison with Liquid-Gas:

- different behavior at T=0 for hadronic matter and nuclei: Fermi-Dirac statistics

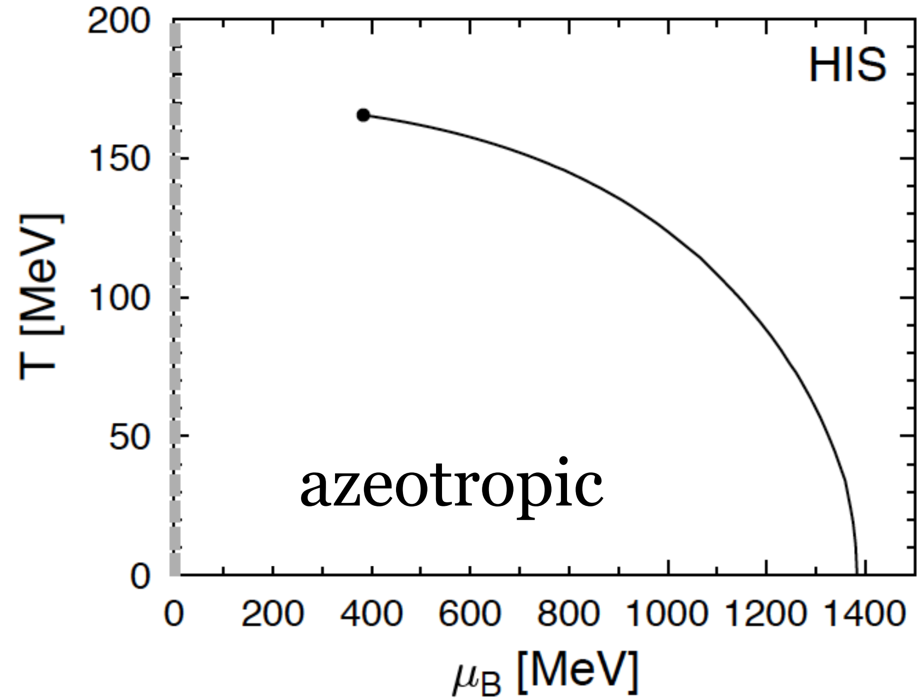
- all features vanish around critical point for deconfinement phase transitions

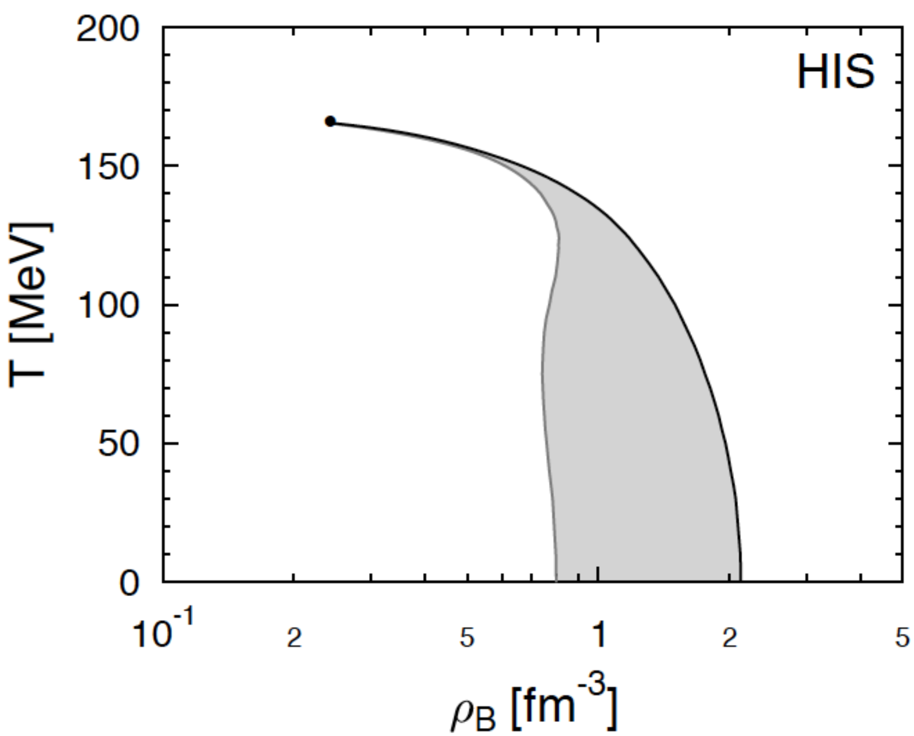


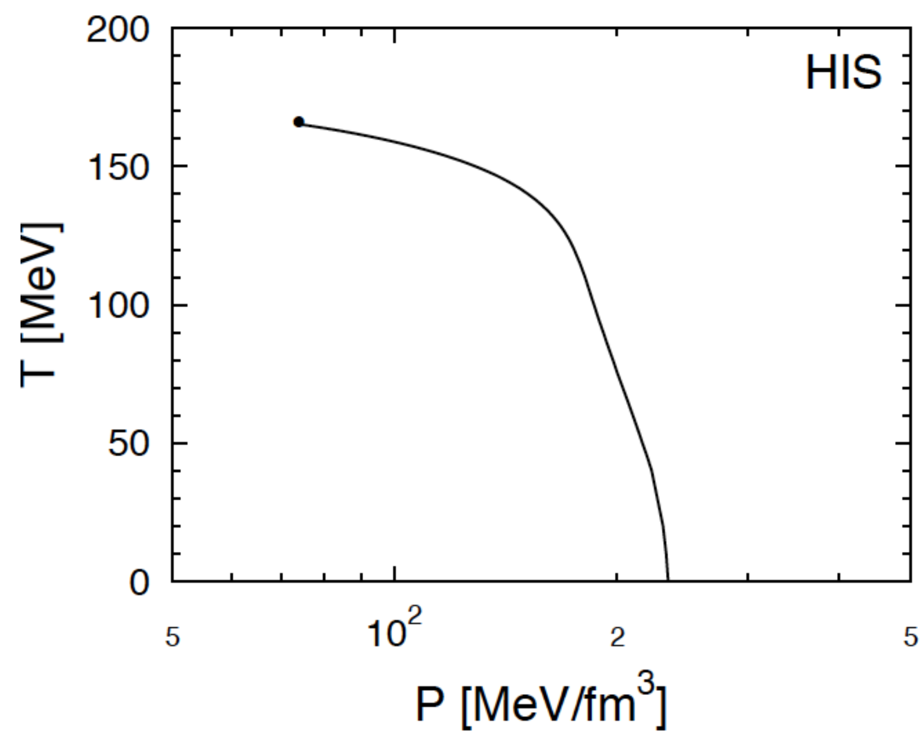


⭑ Symmetric Matter:

- heavy ion collisions (S=0)
- more than one conserved charge (baryon #, isospin) but a congruent phase transition! (μ_q=0)
- dP/dT < 0

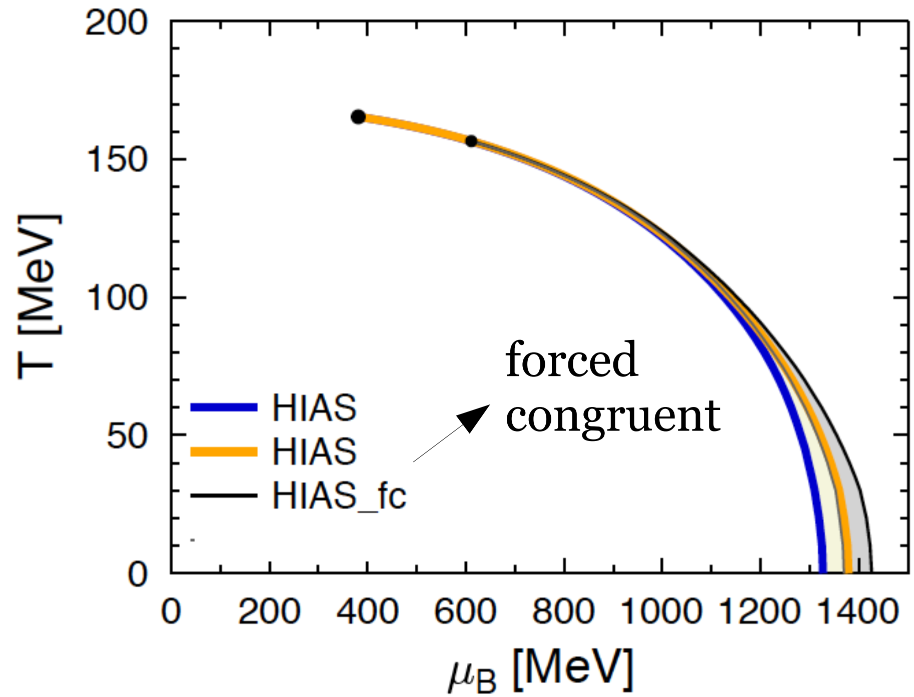


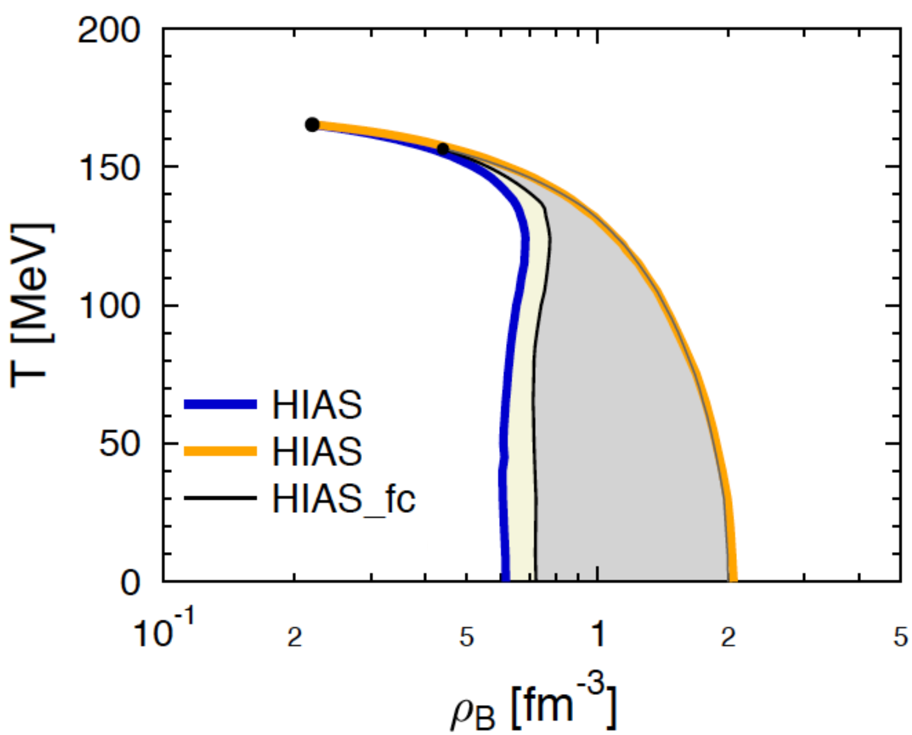


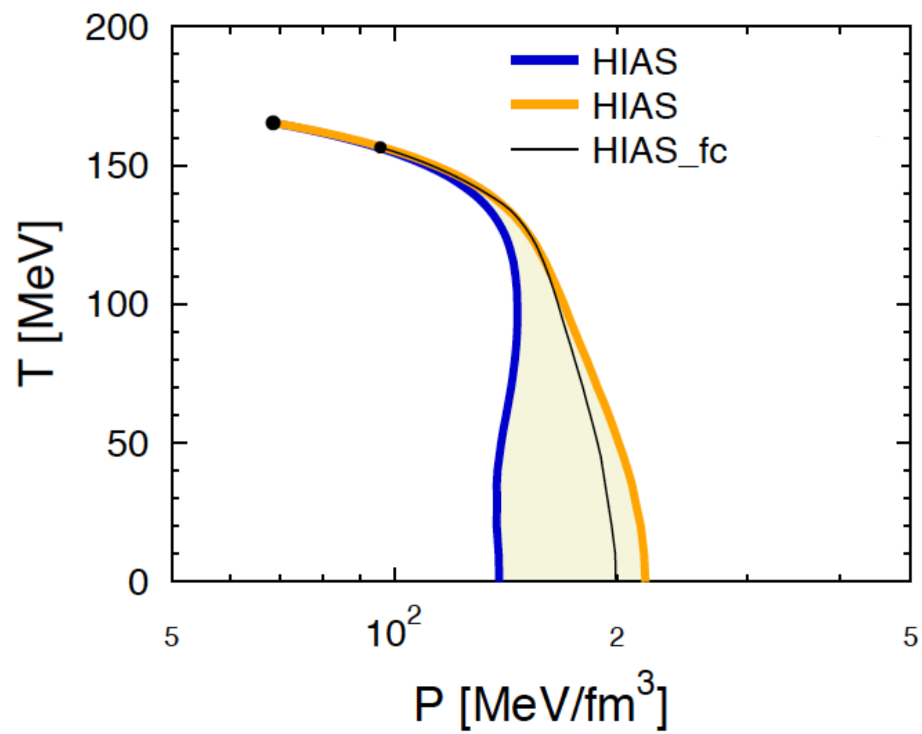


⭑ Asymmetric Matter:

- HI with Y_Q=0.3
- more than one conserved charge (baryon #, charge fraction) non-congruent phase transition!
- dP/dT < 0?





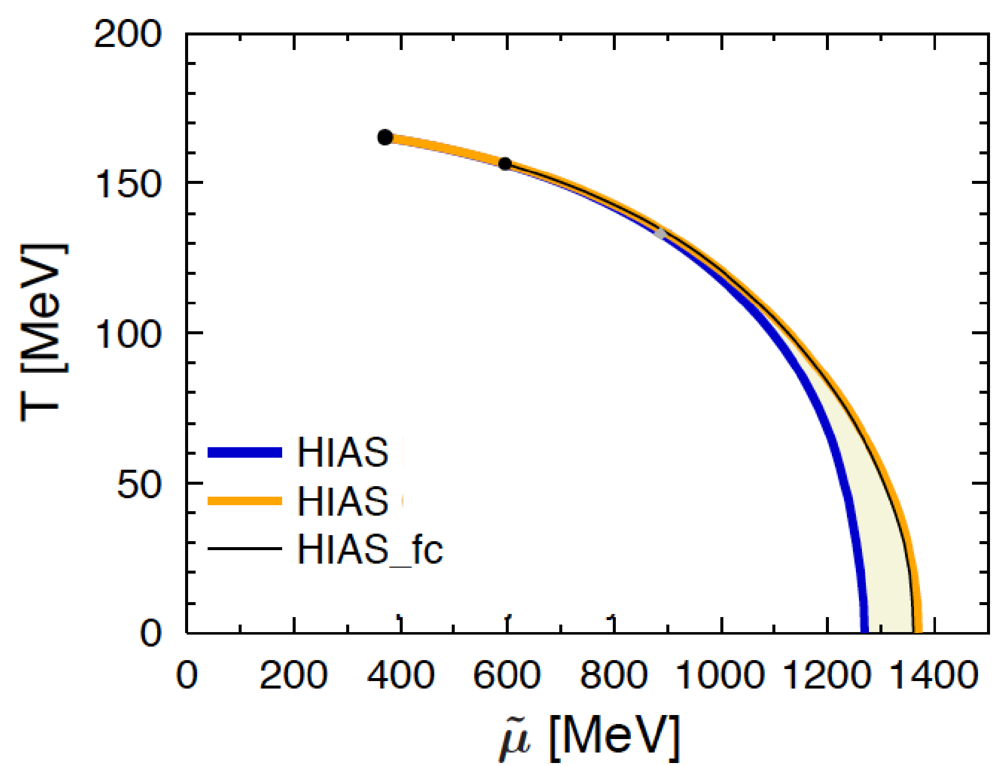


✯ Modified Chemical Potential:

- in mixture of phases $\tilde{\mu} = Y_Q \mu_Q + \mu_B$, since $\tilde{\mu}^I = \left.\frac{\partial F^I}{\partial B^I}\right|_{T,V^I,S^I,Y_Q^I}$ is the only chemical potential which is the same in both phases (fc case)

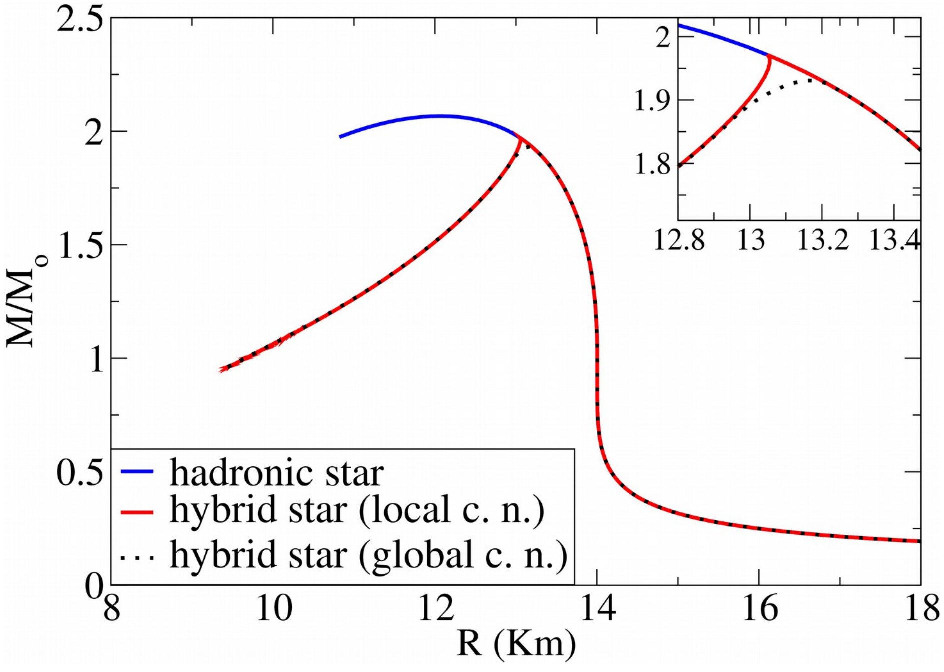
$$= \mu_B^I + Y_Q^I \mu_Q^I \ ,$$

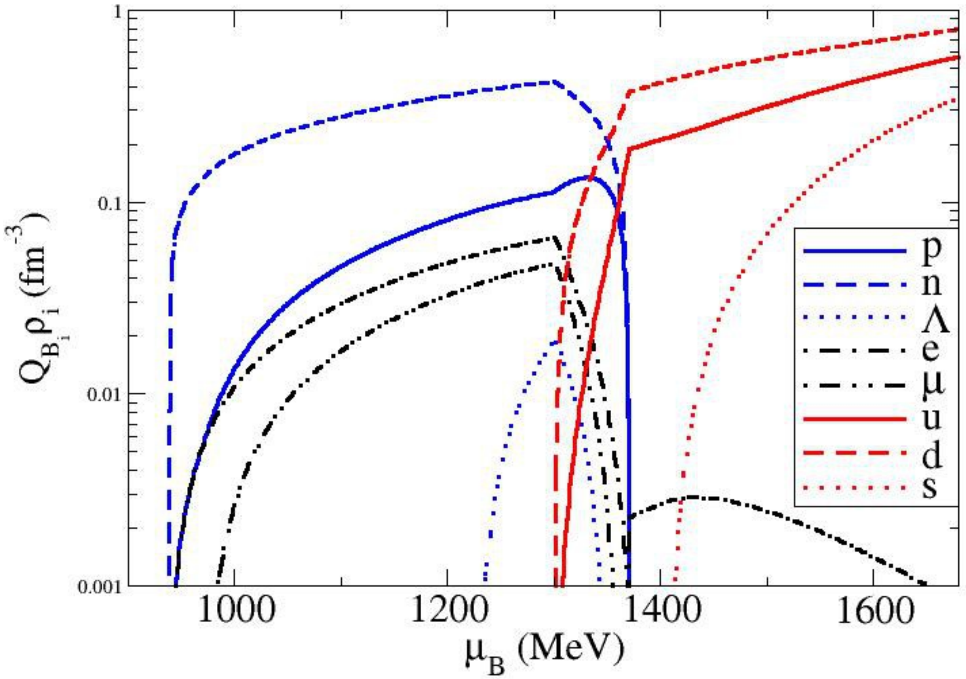
- important around phase transition
- HI forced congruent inside mixed region
- not relevant for charge neutral case



✯ Test 1: Hydrostatic Equilibrium

- hyperon suppression
- hybrid massive stars
- no stable star with pure quark matter
- mixed phase of up to 2 km in star





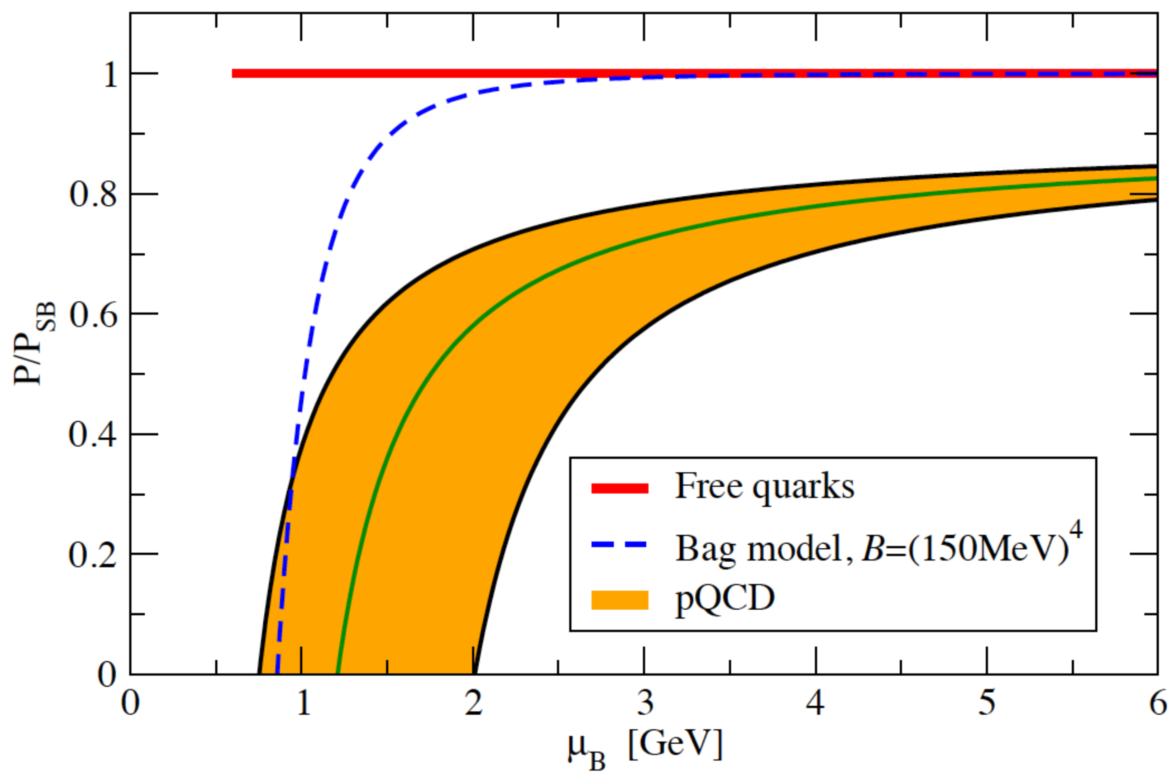
⋆ Perturbative QCD:

- figure from: Fraga, Kurkela and Vuorinen, Astrophys. J. 2014

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

- band reflects uncertainties

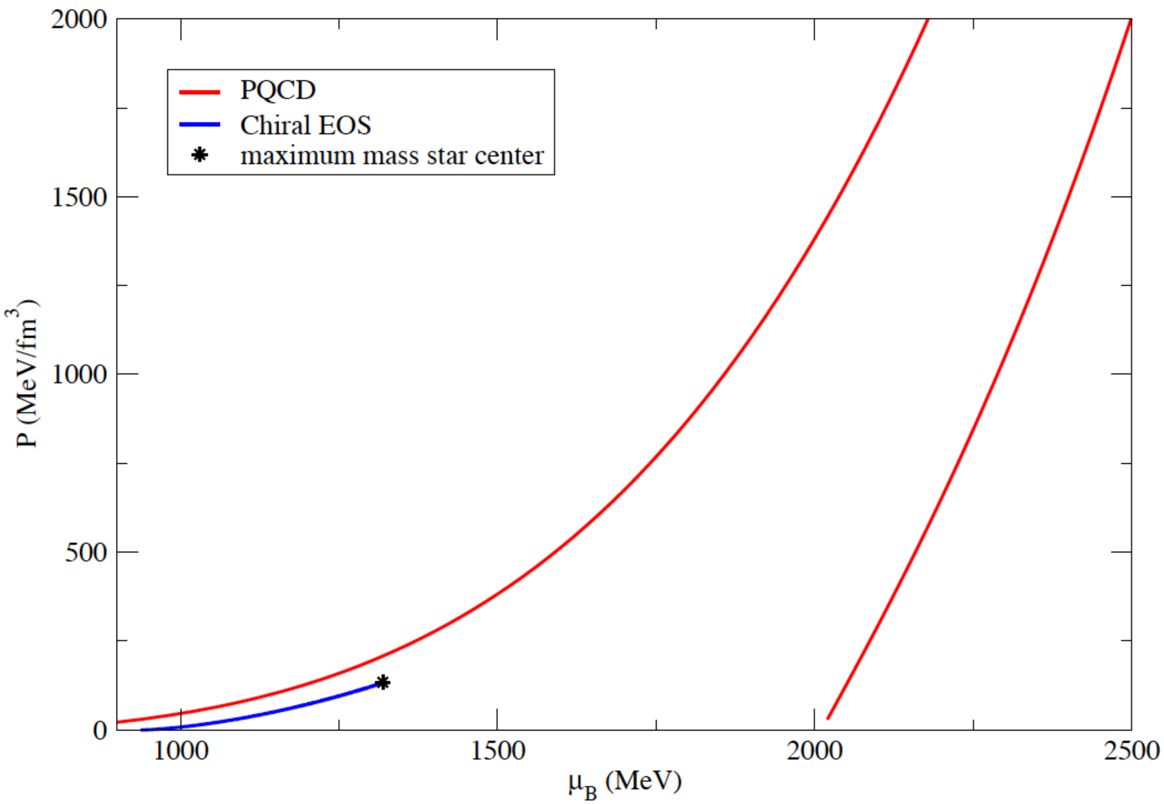
- Bag model failure



Test 2: Perturbative limit comparison

- for T=0 things look good!

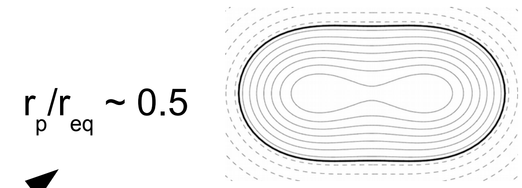
- larger temperature results coming soon ...



⭑ For fun: Maxwell-Einstein Equations (Lorene)

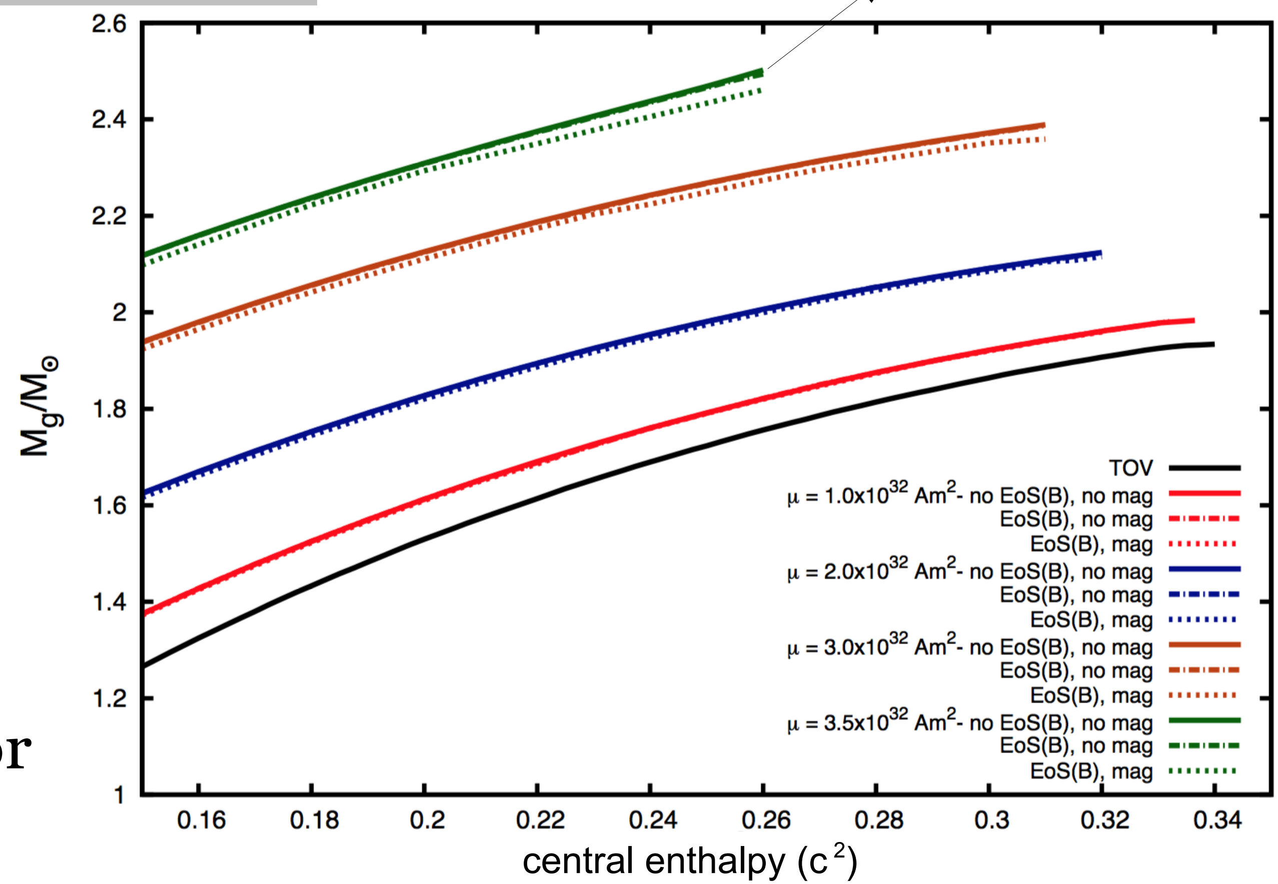
- axisymmetric poloidal magnetic field

Bonazzola et al. Astron. Astrophys. 1993



- 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

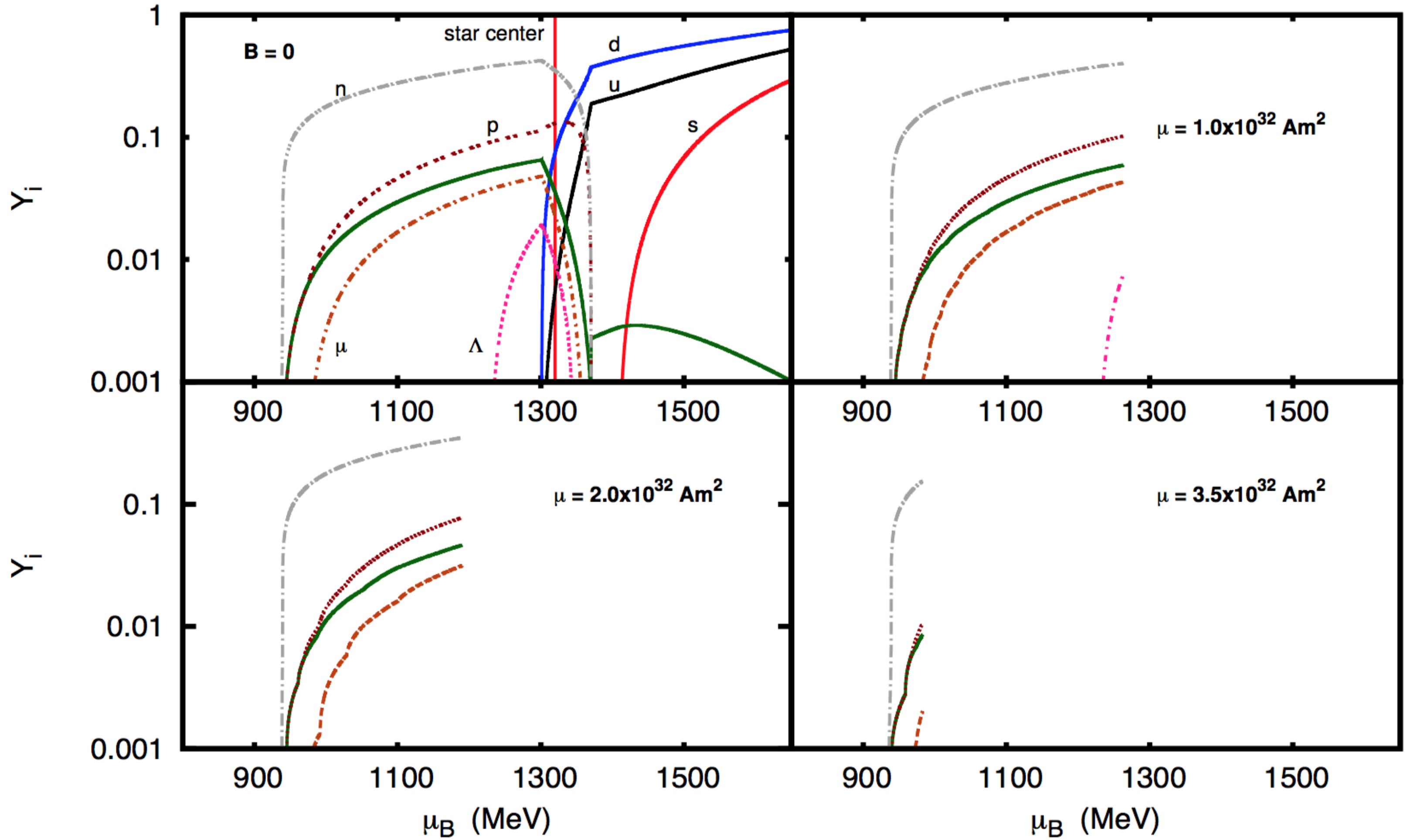


Franzon et al. Mon. Not. Roy. Astron. Soc. 2016

⭑ Population

- different compositions for different magnetic dipole moments μ (magnetic field distributions) at fixed baryon mass

- magnetic field decay accompanied by deconfinement?



Conclusions and Outlook

- More investigation of high density part of phase diagram is required! Signature for 1st order phase transition?

- Description of compact stars requires finite temperature description

- We need a realistic EOS that covers large portion of phase diagram and provides population for simulations: only a unified EOS (usually used for L-G transitions) description of phases can provide critical points and crossovers

- congruent/not-congruent deconfinement phase transitions still being understood

- magnetic fields modify the structure and population of stars

- we still need to include neutrino trapping at finite temperature

- we still need to include magnetic field effects at finite temperature

- we still need to include quark pairing effects