Phase Transitions in Dense Matter

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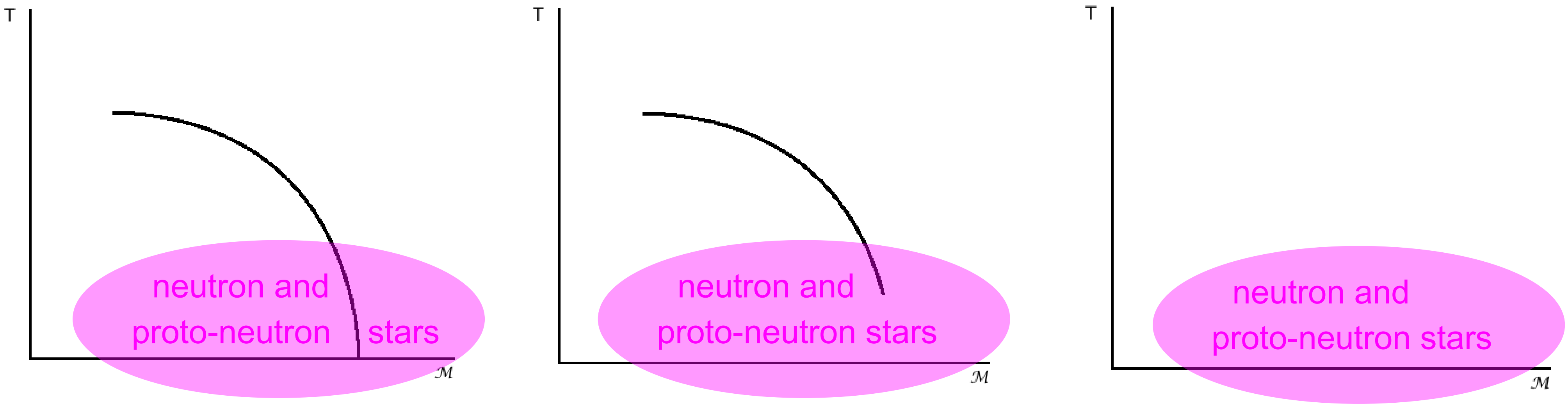
✯ Motivation:

- very little information about the QCD phase diagram at zero or low temperature

  - strength of transition
  - population (required for cooling simulations, etc)



⋆ CMF (Chiral Mean Field) Model:

- extended non-linear realization of SU(3) sigma model
- uses pseudo-scalar mesons as parameters of chiral transformation
- includes baryon octet, leptons and quarks
- fitted to reproduce nuclear, lattice QCD and astrophysical constraints
- effective masses

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

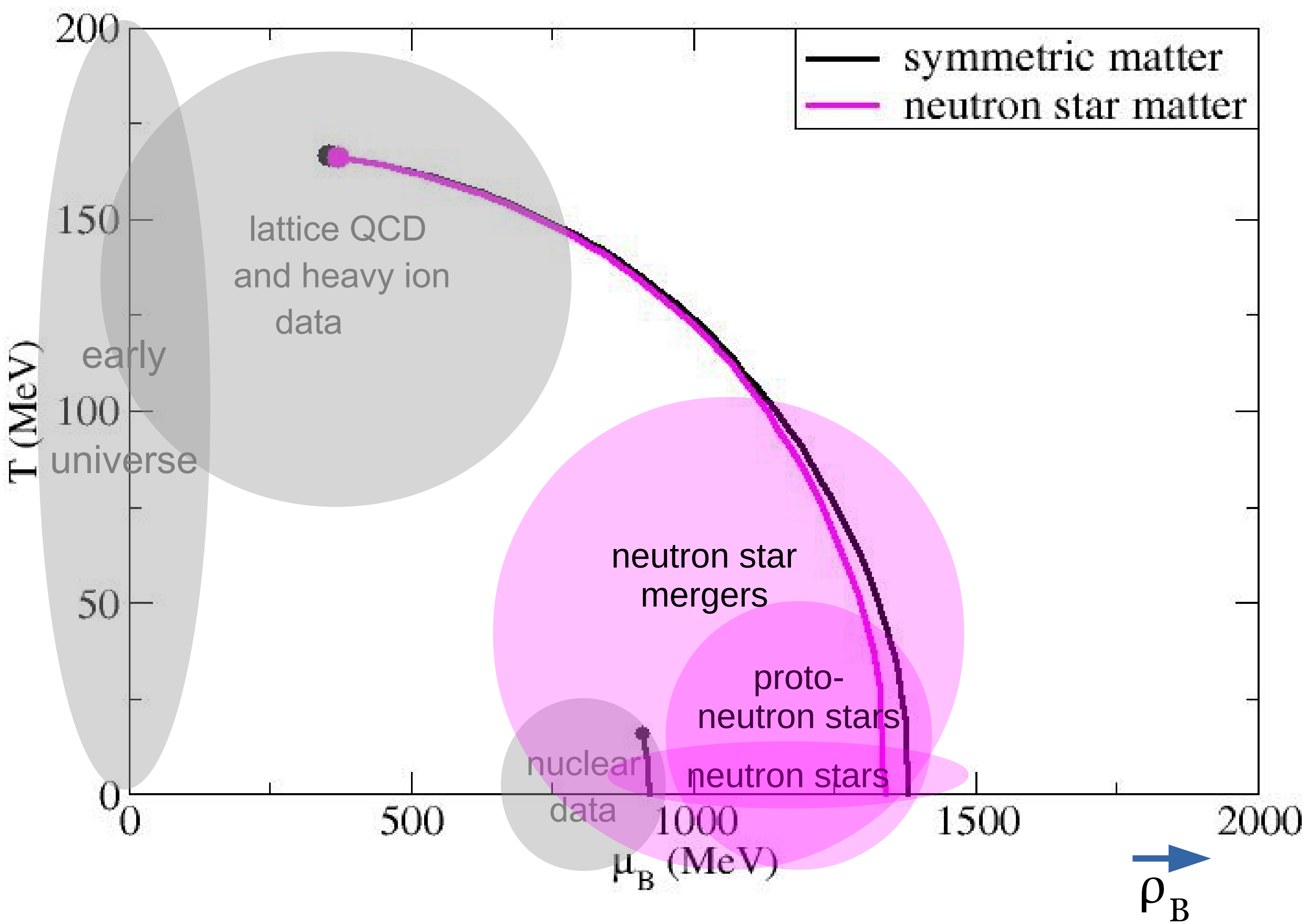
- 1st order phase transitions or crossovers (order parameters σ,Φ)

- potential for Φ (deconfinement)

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

✫ General Picture:

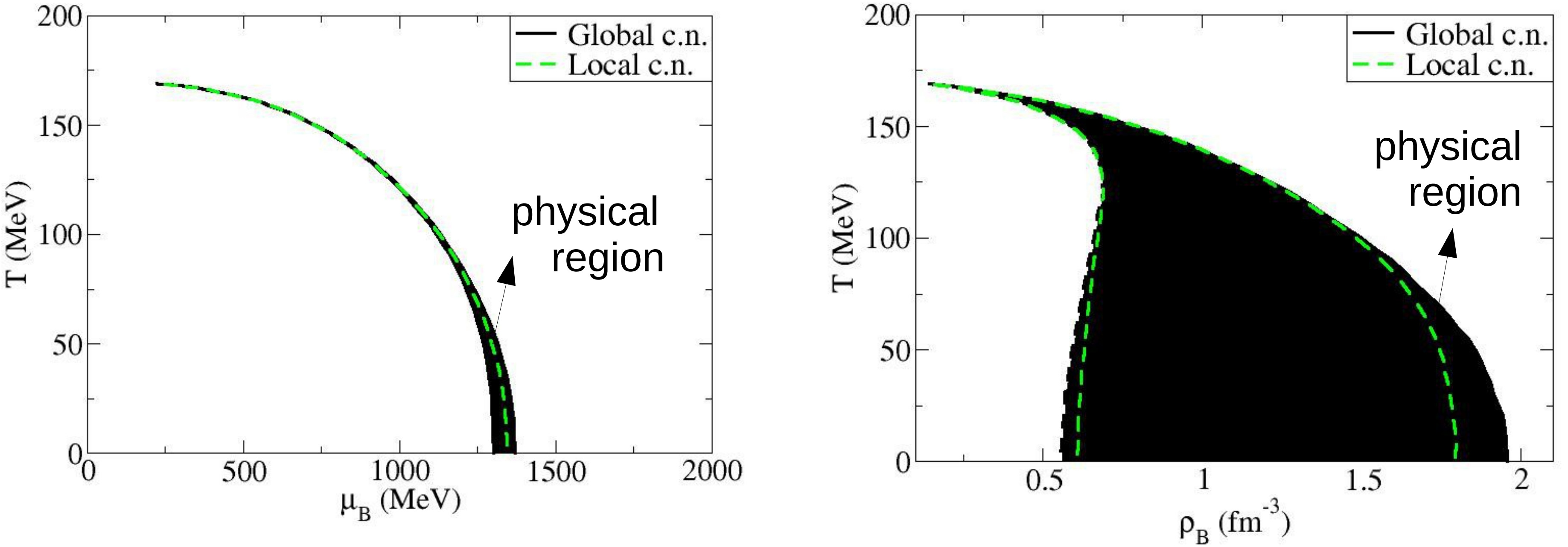
Dexheimer et al. Phys. Rev. C 2010



✯ Neutron Star Matter: Local and Global Charge Neutrality:

- absence / presence of mixture of phases: surface tension ???

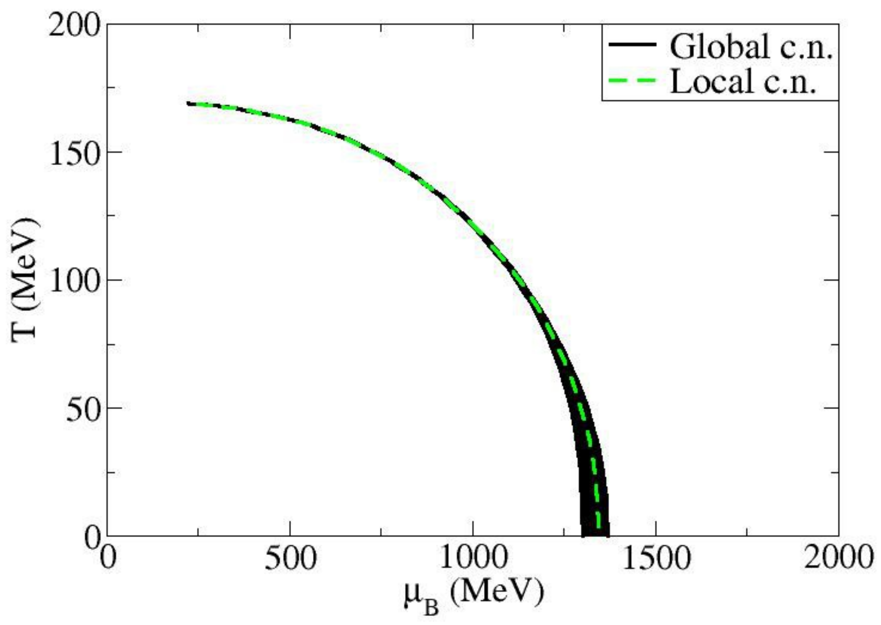
- “mixed” quantities like $\rho_B = \lambda \rho_B^Q + (1-\lambda)\rho_B^H$

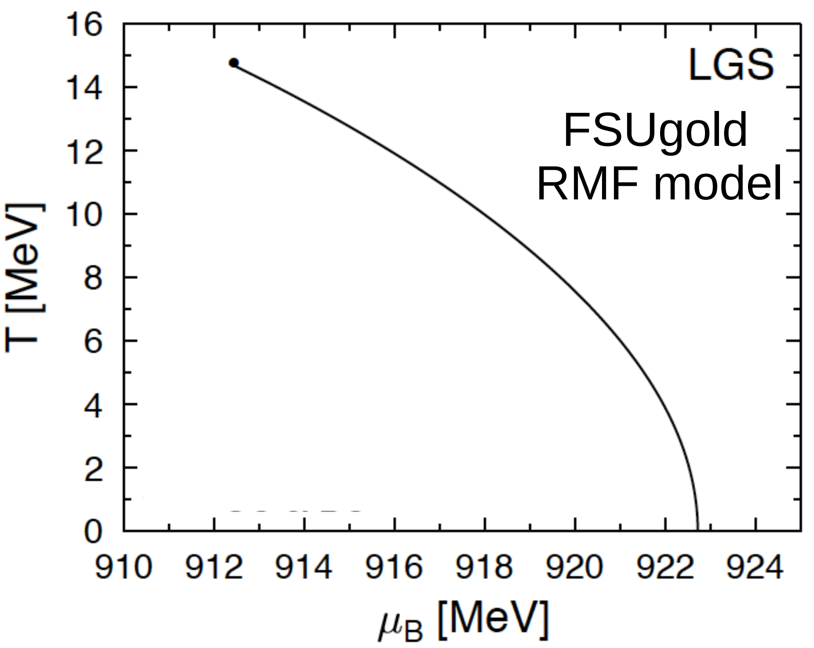


Hempel et al. Phys. Rev. C 2013

✭ Non-congruent Phase Transitions:

- more than one globally conserved charge within 2 macroscopic phases (in a Coulomb-less model): baryon #, electric charge
- local concentration of charge varies during phase transition
- same chemical potential (assoc. to charge) in both phases (μ_q)
- non-congruent features vanish around critical point
- different from symmetric matter liquid-gas





✯ More Comparison with Liquid-Gas:

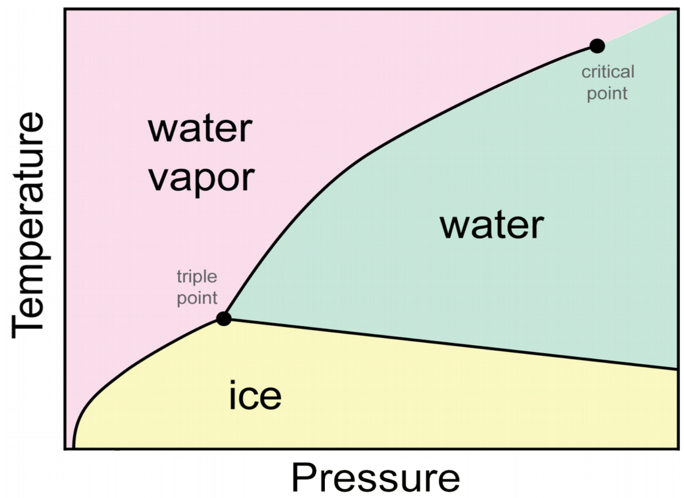
- Clausius-Clapeyron equation $$\frac{dP}{dT} = \frac{s^I - s^{II}}{1/\rho_B^I - 1/\rho_B^{II}}$$

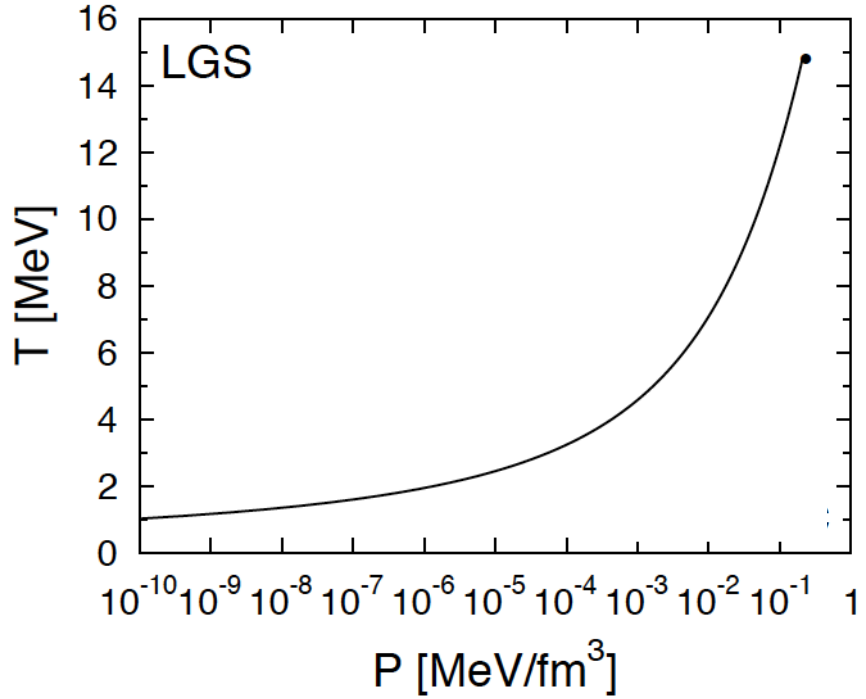
- $s_q^{II} > s_h^I$, $\rho_{Bq}^{II} > \rho_{Bh}^I$

  so $dP/dT < 0$ for deconfinement!

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

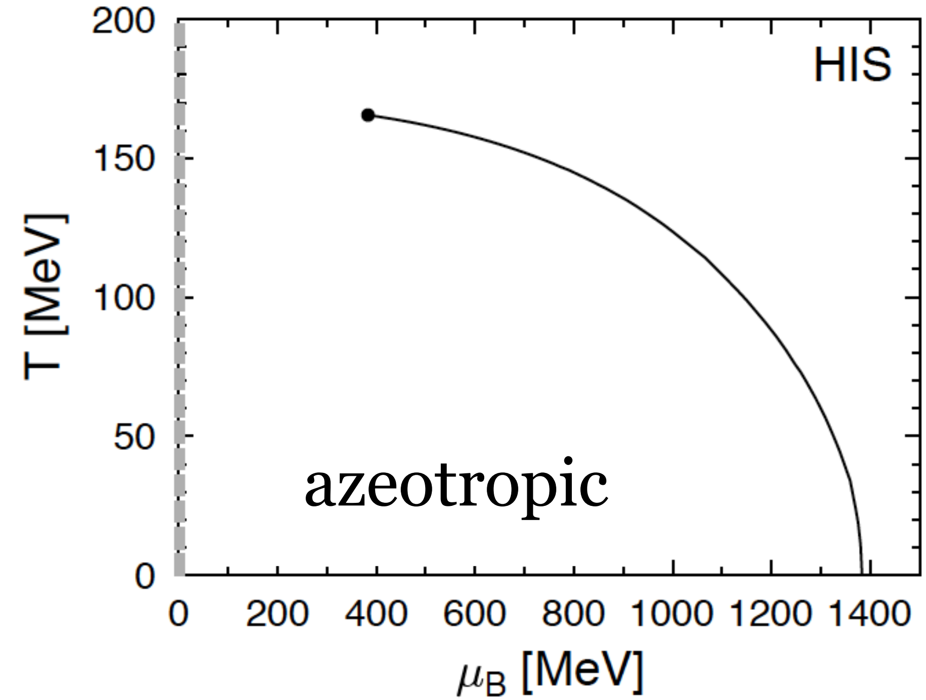
  so $dP/dT > 0$ for L-G!

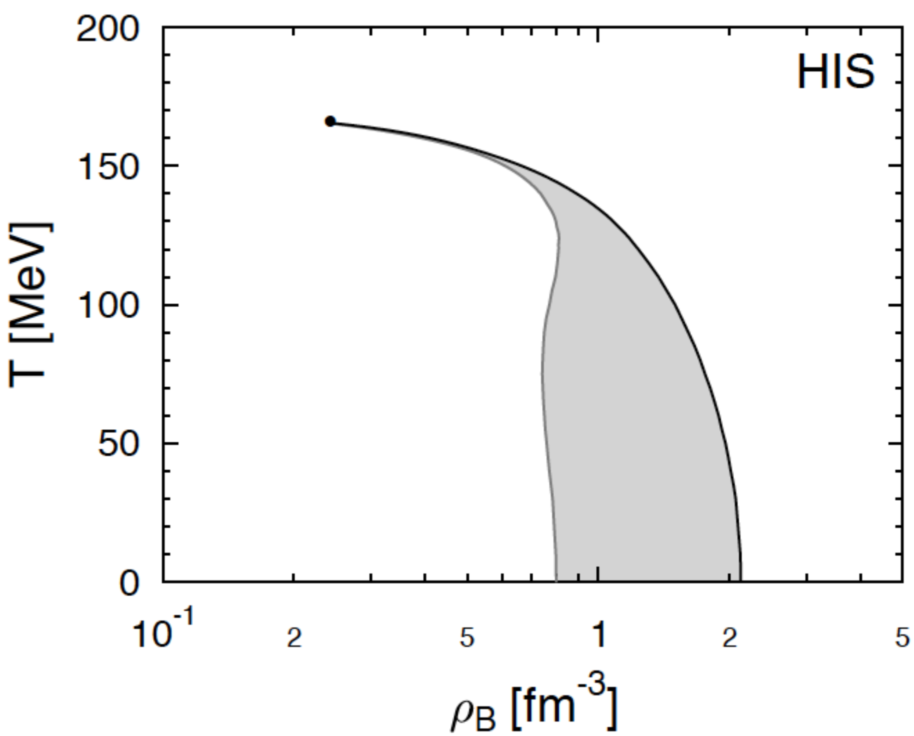


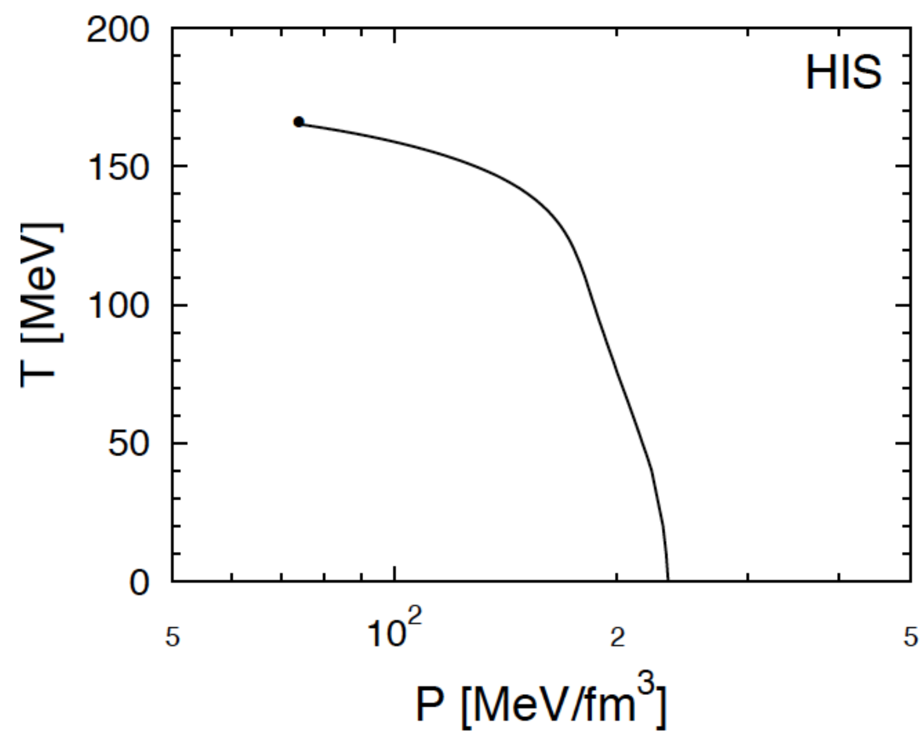


⋆ Symmetric Matter:

- heavy ion collisions (no net strangeness)
- more than one conserved charge (baryon #, isospin) but congruent phase transition! (μ_q=0)

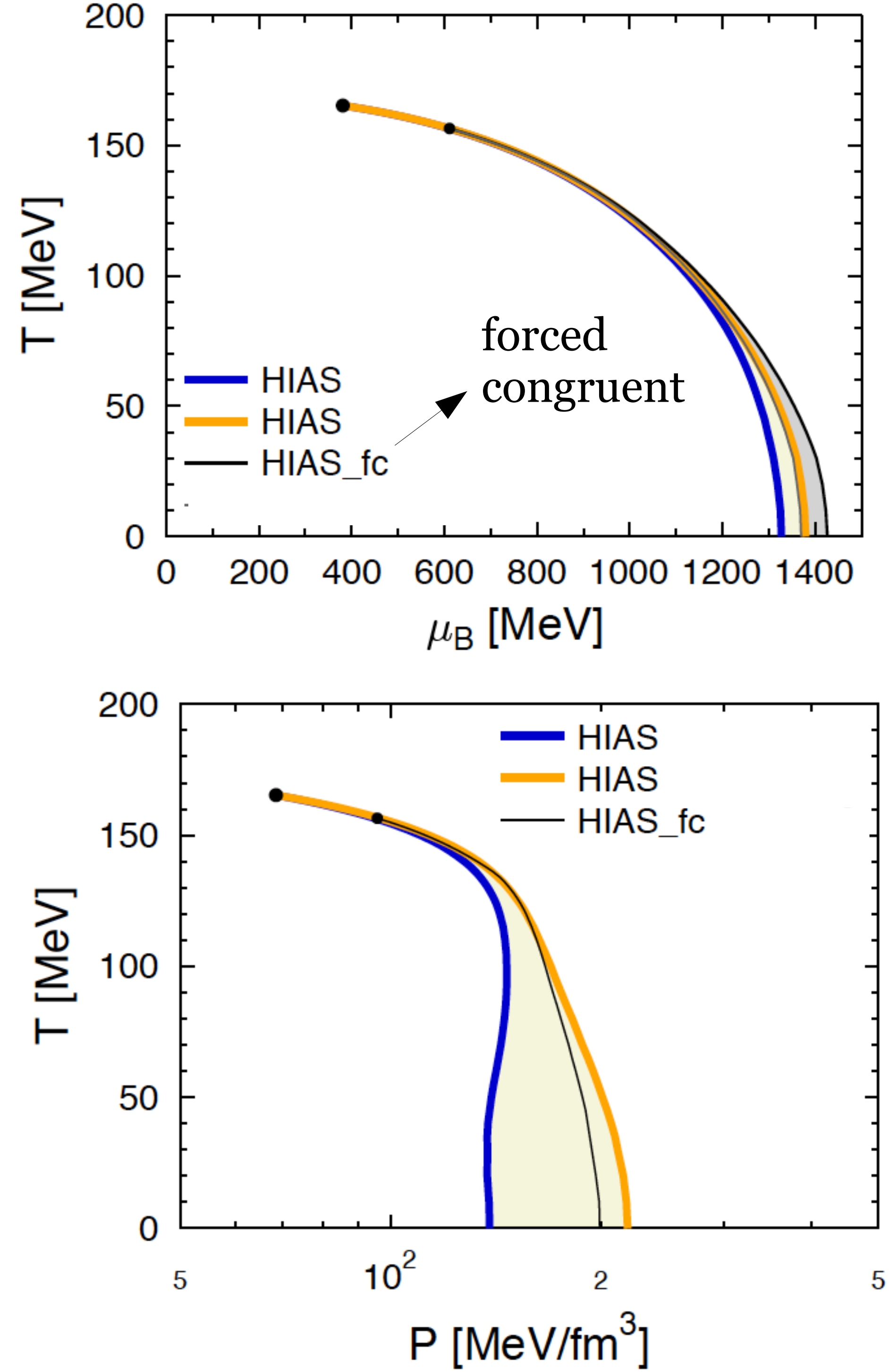






✯ Asymmetric Matter:

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

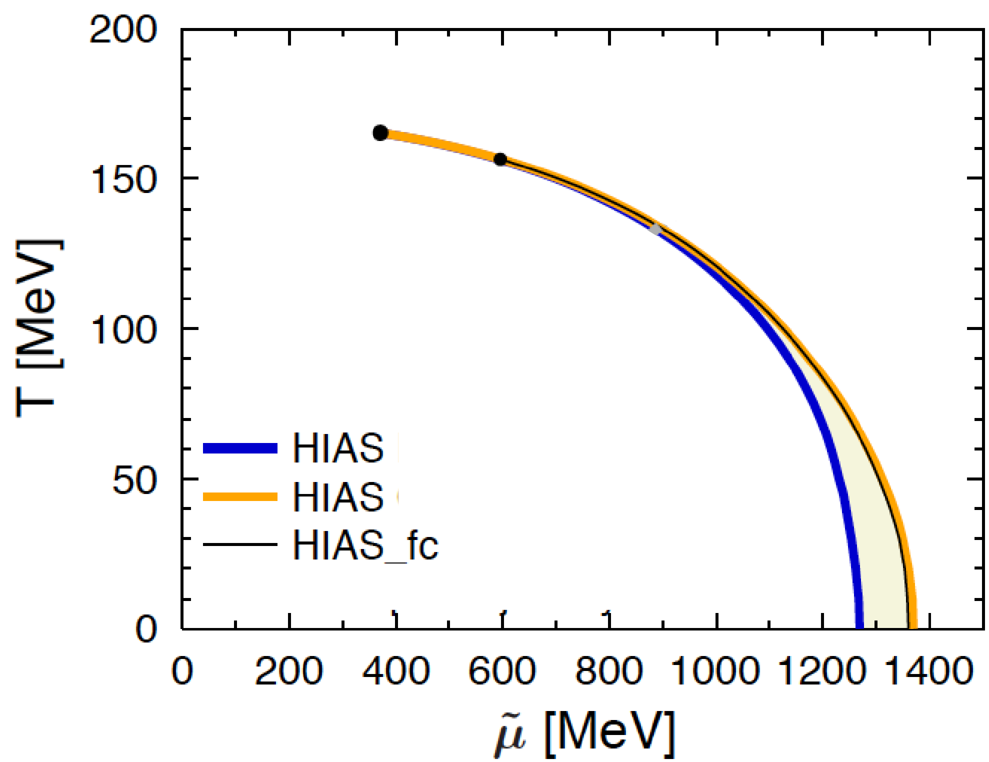


⋆ Modified Chemical Potential:

- in mixture of phases $\tilde{\mu} = Y_Q \mu_Q + \mu_B$, since is the only chemical potential which is the same in both phases

$$\tilde{\mu}^I = \left. \frac{\partial F^I}{\partial B^I} \right|_{T,V^I,S^I,Y_Q^I} = \mu_B^I + Y_Q^I \mu_Q^I \ ,$$

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



Conclusions and Outlook

- More investigation of high density part of phase diagram is required!
  Astrophysical 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 and might have associated signatures

- 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

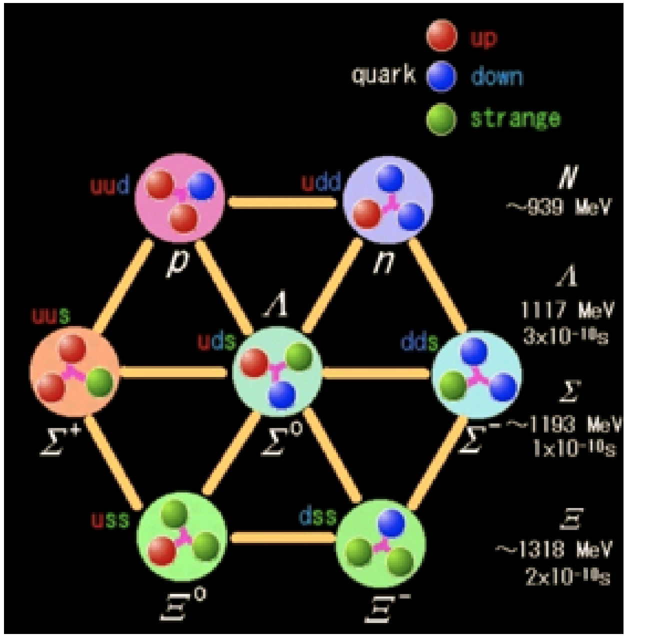
⋆ Ingredients for Core Description:

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

- leptons ensure charge neutrality: e, μ

- amount of each particle not constant (chemical equilibrium)

- nuclear physics constraints



- vacuum masses of baryons and mesons
- pion and kaon decay constants
- saturation density
- binding energy at saturation
- compressibility at saturation
- symmetry energy and derivative at saturation
- hyperon optical potentials at saturation

✯ Non-Linear Realization SU(3) Sigma Model:

- includes baryon octet and leptons

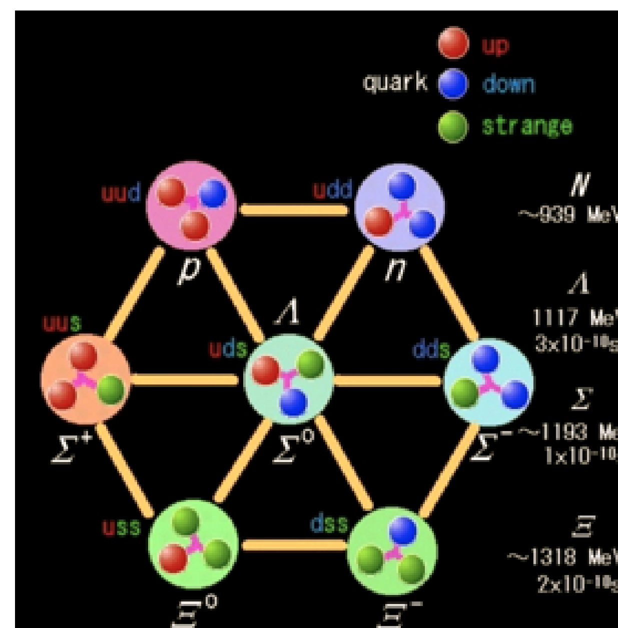
- constructed from symmetry relations → allow it to be chirally invariant → masses from interaction with medium

- pseudo-scalar mesons as parameters of chiral transformation

- σ signals chiral symmetry restoration

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

- fitted to reproduce nuclear and astrophysical constraints



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

⋆ Lagrangian Density in MFT:

$$L = L_{Kin} + L_{Int} + L_{Self} + L_{SB}$$

$$L_{Int} = -\sum_i \bar{\psi}_i[\gamma_0(g_{i\omega}\omega + g_{i\phi}\phi + g_{i\rho}\tau_3\rho) + M_i^*]\psi_i,$$

$$\begin{aligned} L_{Self} = & \frac{1}{2}(m_\omega^2\omega^2 + m_\rho^2\rho^2 + m_\phi^2\phi^2) \\ & + g_4\left(\omega^4 + \rho^4 + \alpha^2\frac{\phi^4}{2} + 3\alpha(\omega^2+\rho^2)\phi^2\right) \\ & - k_0(\sigma^2+\zeta^2+\delta^2) - k_1(\sigma^2+\zeta^2+\delta^2)^2 \\ & - k_2\left(\frac{\sigma^4}{2} + \frac{\delta^4}{2} + 3\sigma^2\delta^2 + \zeta^4\right) - k_3(\sigma^2-\delta^2)\zeta \\ & - k_4 \ \ln\frac{(\sigma^2-\delta^2)\zeta}{\sigma_0^2\zeta_0}, \end{aligned}$$

reproduces vector meson vacuum masses

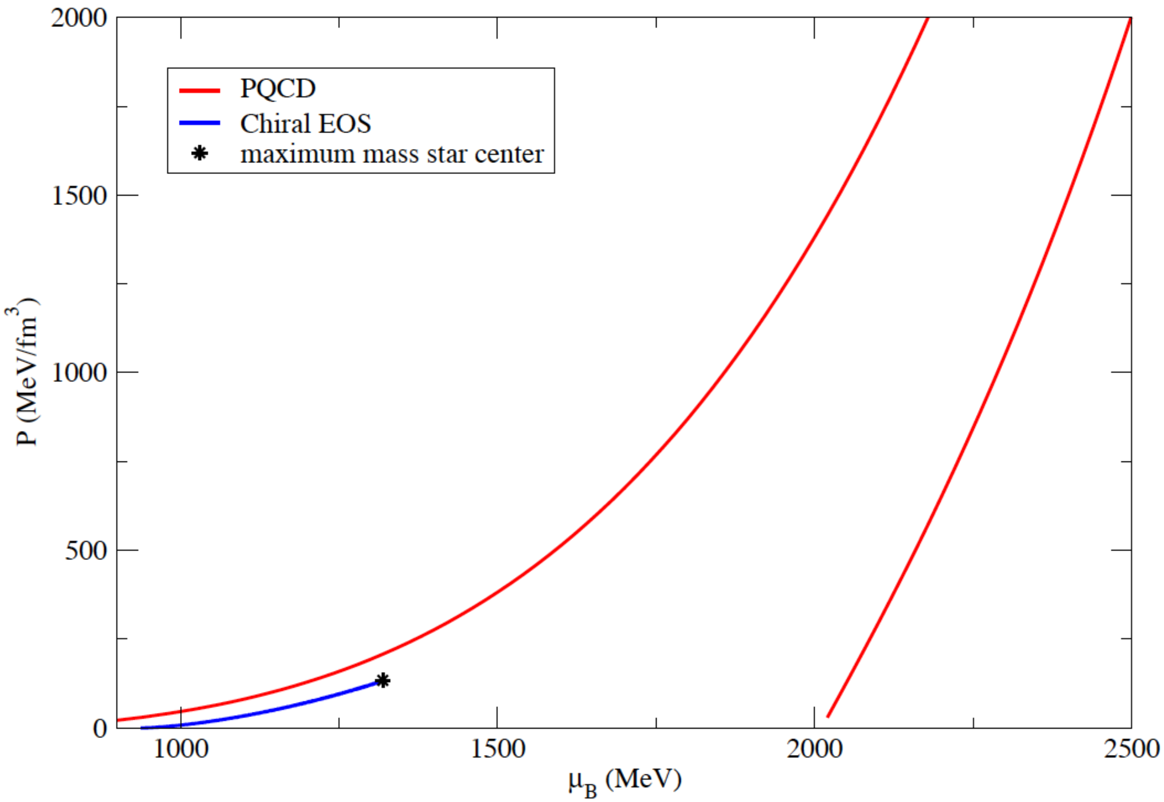
explicit symmetry breaking

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

✯ Perturbative limit comparison

- PQCD data from: Fraga, Kurkela and Vuorinen, Astrophys. J. 2014 for 3-flavor QGP at zero temperature including β-equilibrium and charge neutrality

- For T=0 things look good! Larger temperature results coming soon ...



⋆ 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