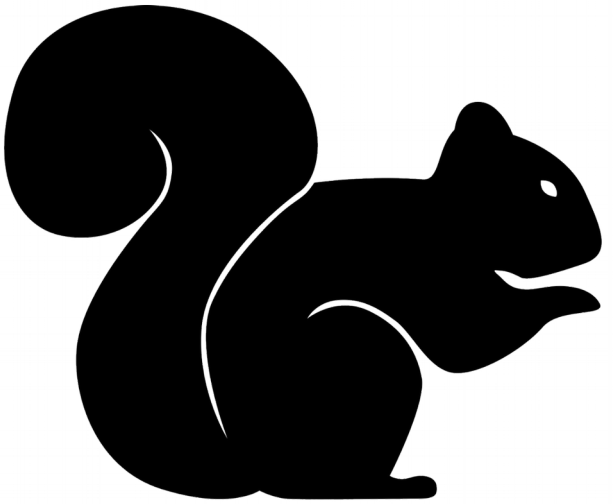
Realistic Equation of State for Neutron Star Mergers



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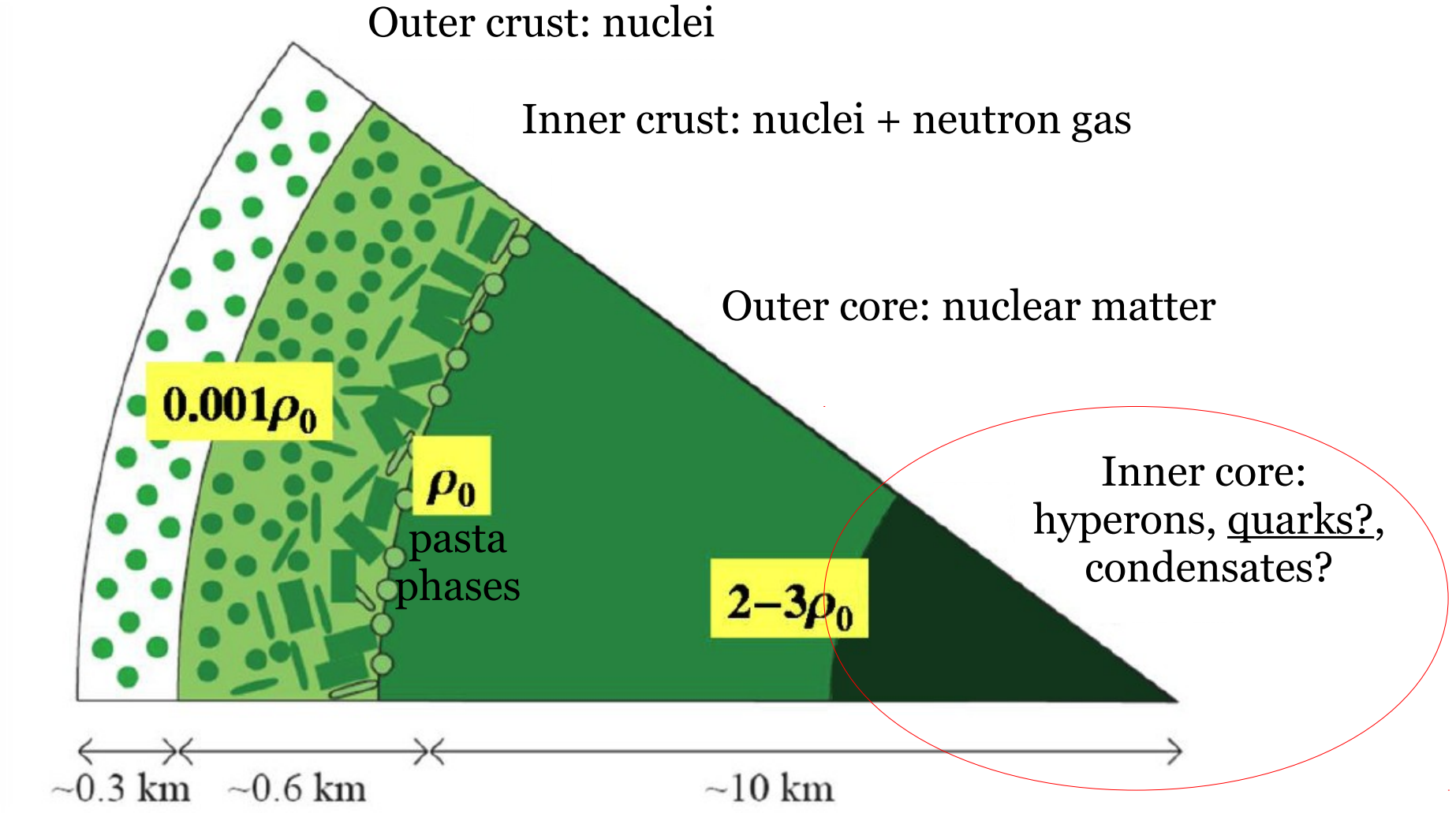
Phys.Rev. C81 (2010) 045201
Phys.Rev. C88 (2013) 014906
Publ. Astron. Soc. Aust. 34 (2017) e066
ArXiv 1803.02411 (Mar 2018)

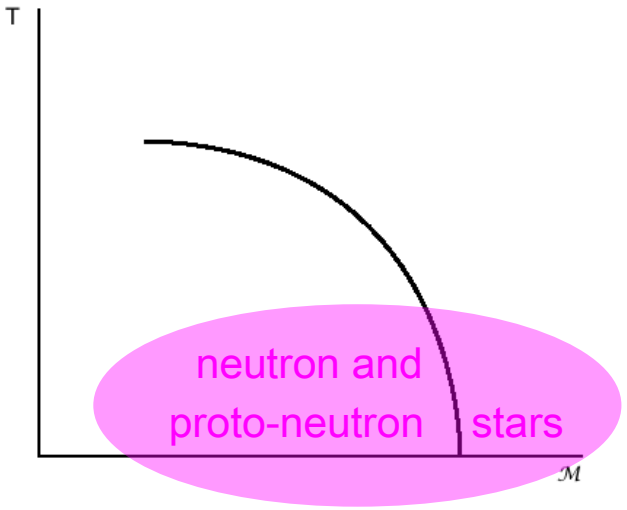
Neutron Star Structure:

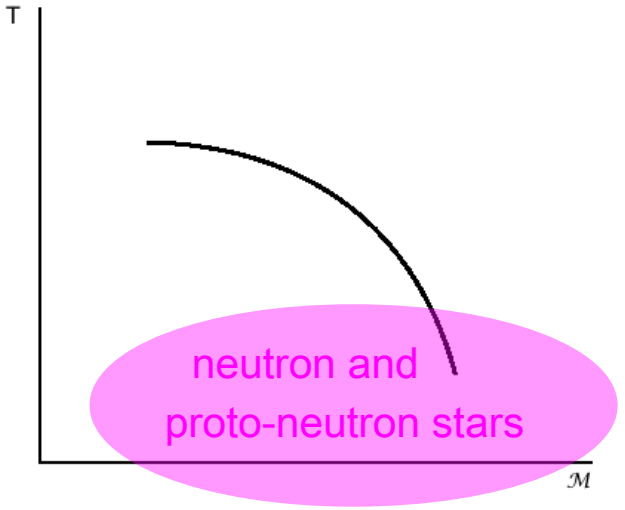


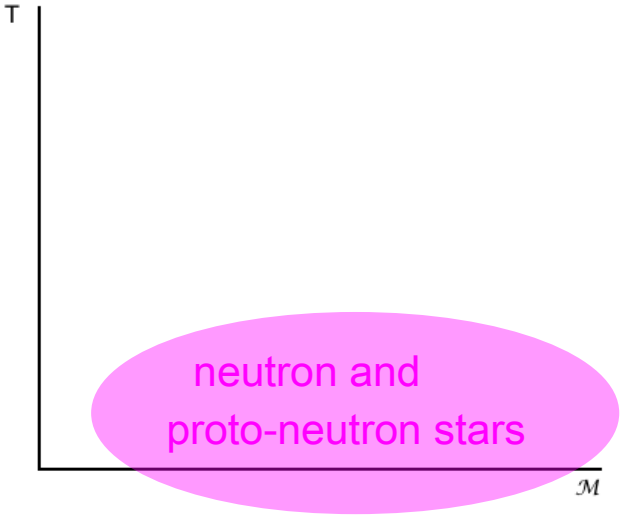
- nuclear saturation density $\rho_0 \sim 0.15$ fm^{-3} (0.25×10^{15} g/cm^3)

QCD Phase Diagram:

- very little information at low temperature
  - strength of transition
  - population

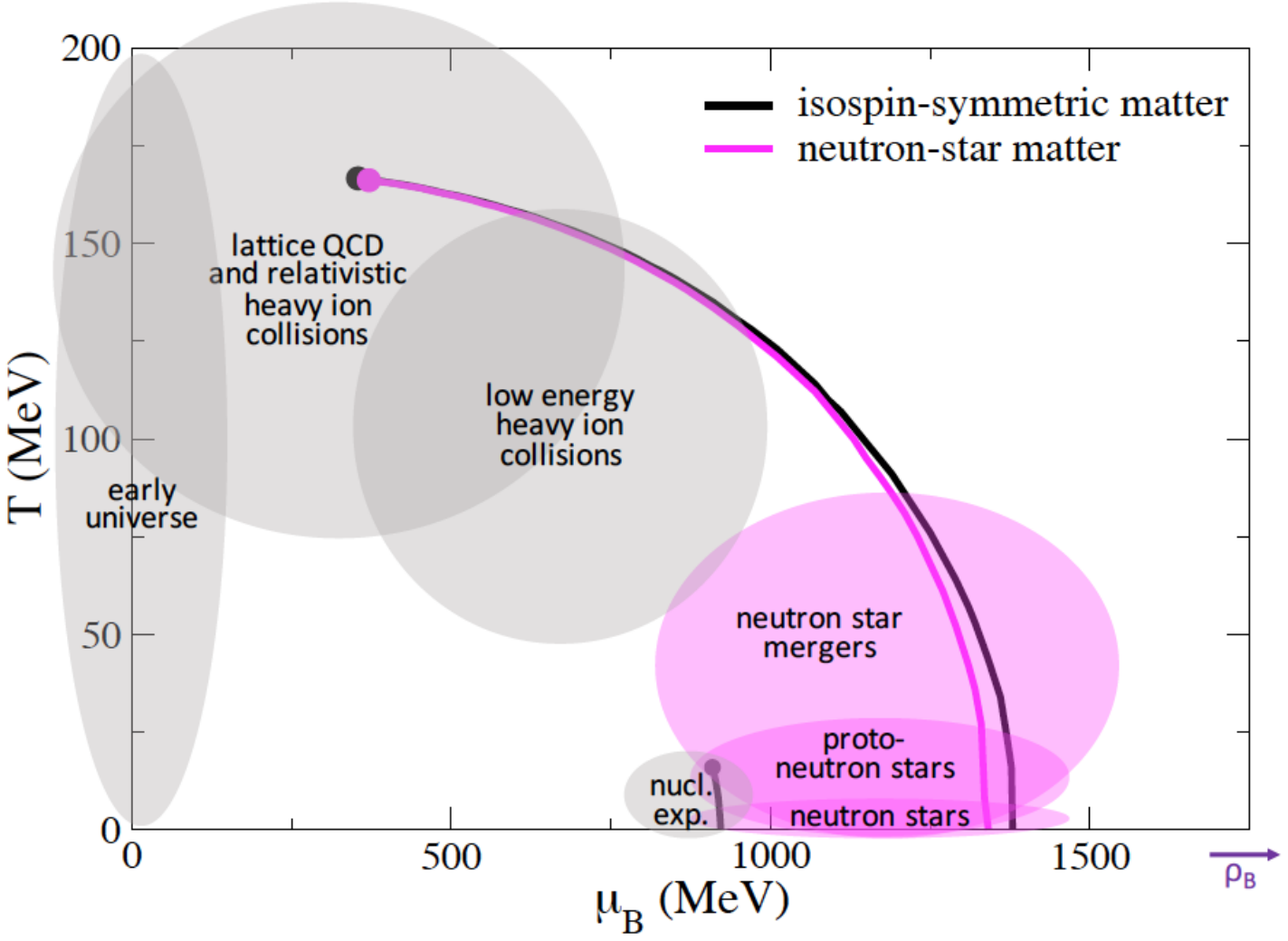






- neutron star mergers?

Assuming Continuous Line:



- results from CMF model (no mixtures of phases)

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

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

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

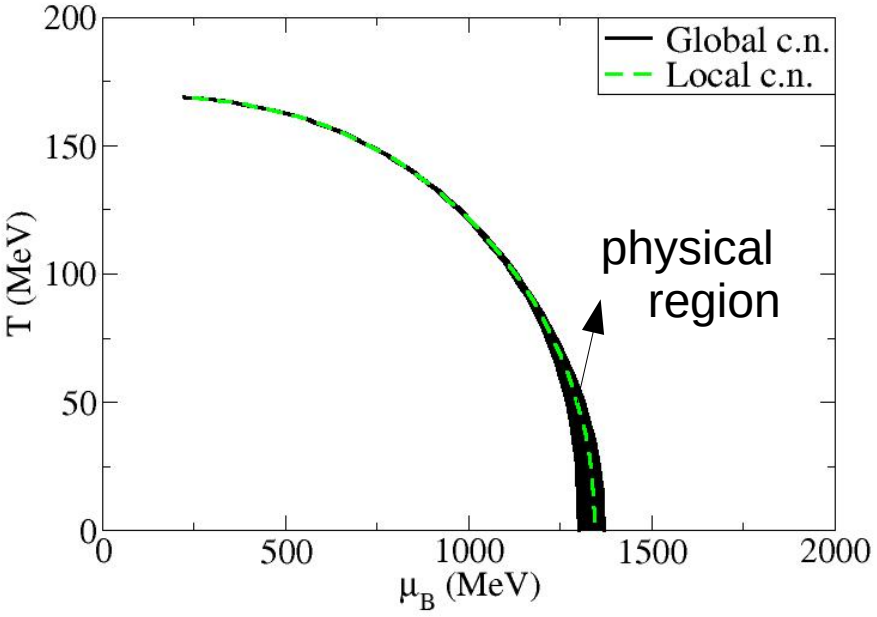
- 1st order phase transitions or crossovers (order parameters σ, Φ)
- potential for Φ (deconfinement)

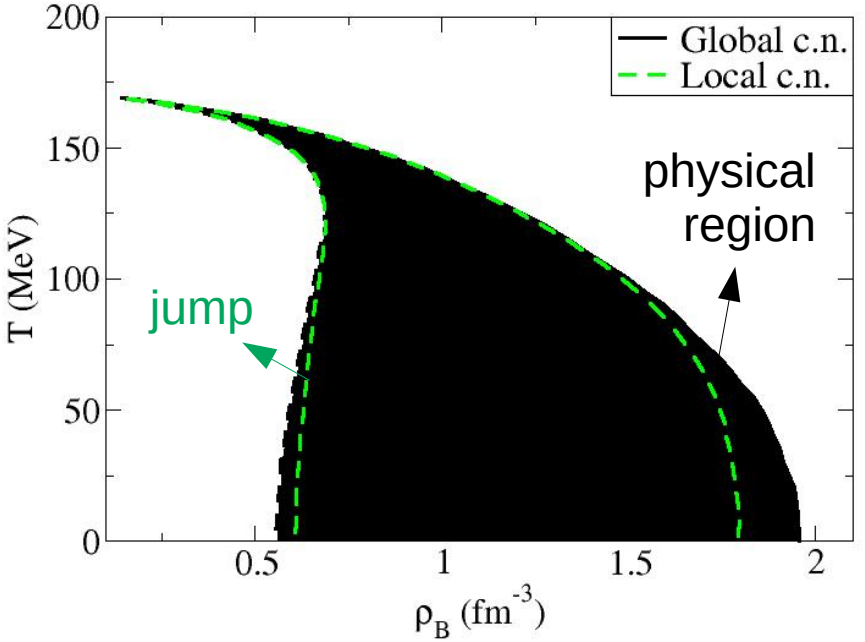
$$U = (a_0\, T^4 + a_1\, \mu^4 + a_2\, T^2\mu^2)\phi^2 + a_3\, T_0^4 \quad \ln(1 - 6\phi^2 + 8\phi^3 - 3\phi^4)$$

Neutron Star Matter: Local vs Global Charge Neutrality:

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

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





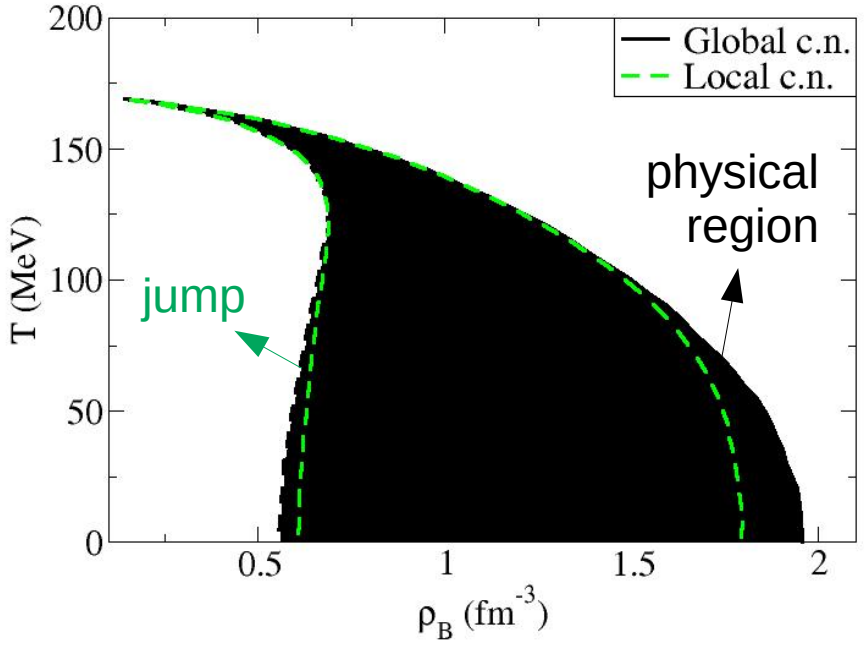
Non-congruent Phase Transitions:

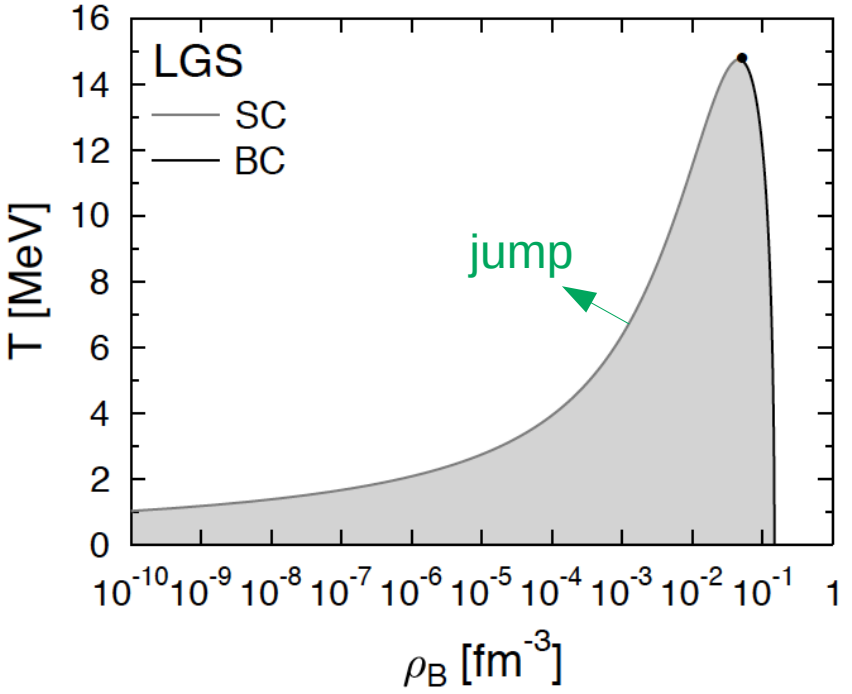
- more than one globally conserved charge within 2 macroscopic phases within a Coulomb-less model: baryon #, electric charge

- local concentration of a charges vary during phase transition

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

- very different from symmetric matter liquid-gas (LGS)





More Comparisons with Nuclear L-G:

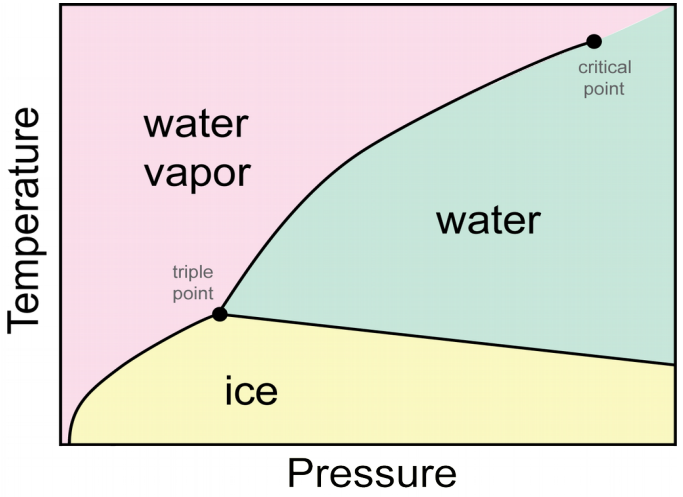
- Clausius-Clapeyron equation $$\frac{dP}{dT} = \frac{s^I - s^{II}}{1/\rho_B^I - 1/\rho_B^{II}}$$

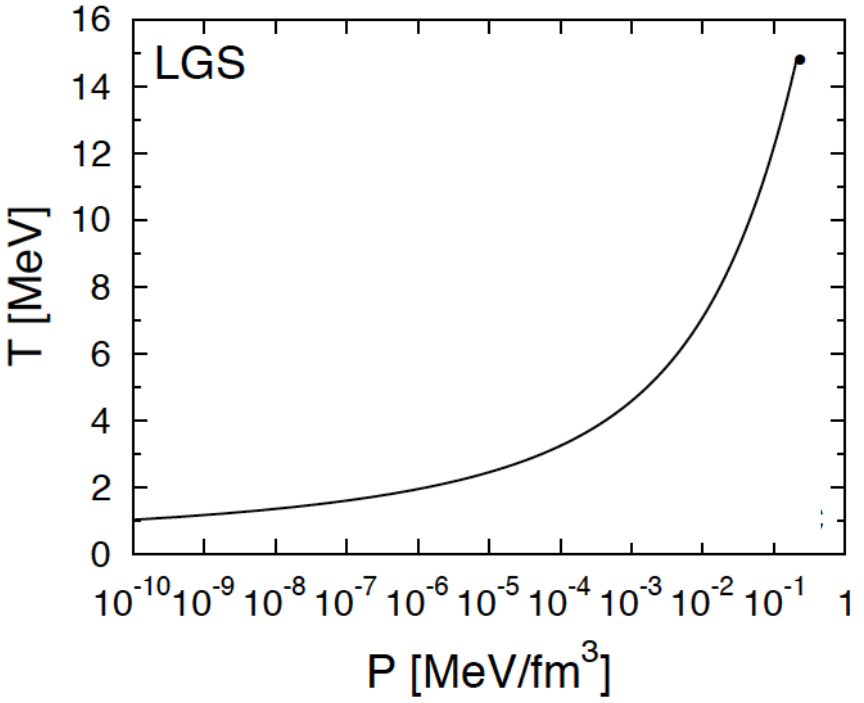
- $s_q^{II} > s_h^I$, $\rho_{Bq}^{II} > \rho_{Bh}^I$

  so dP/dT < 0 for deconfinement!

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

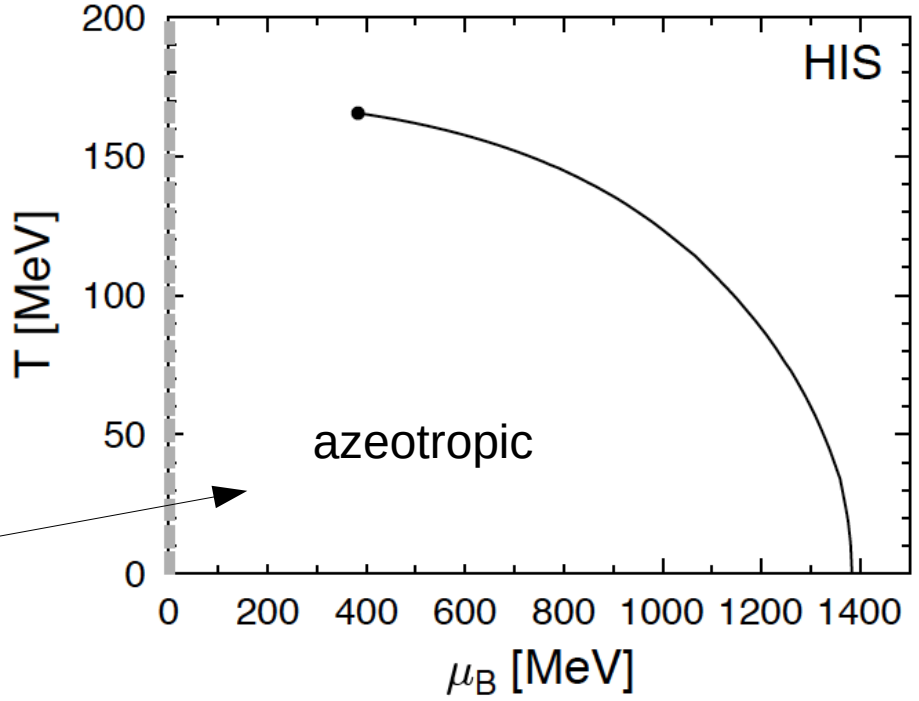
  so dP/dT > 0 for LGS

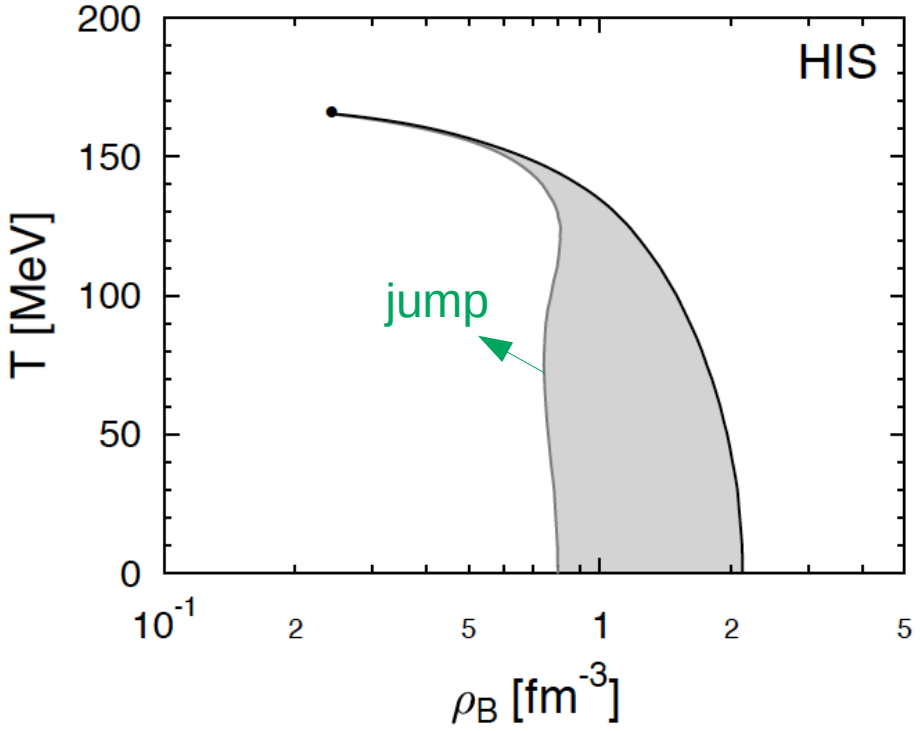


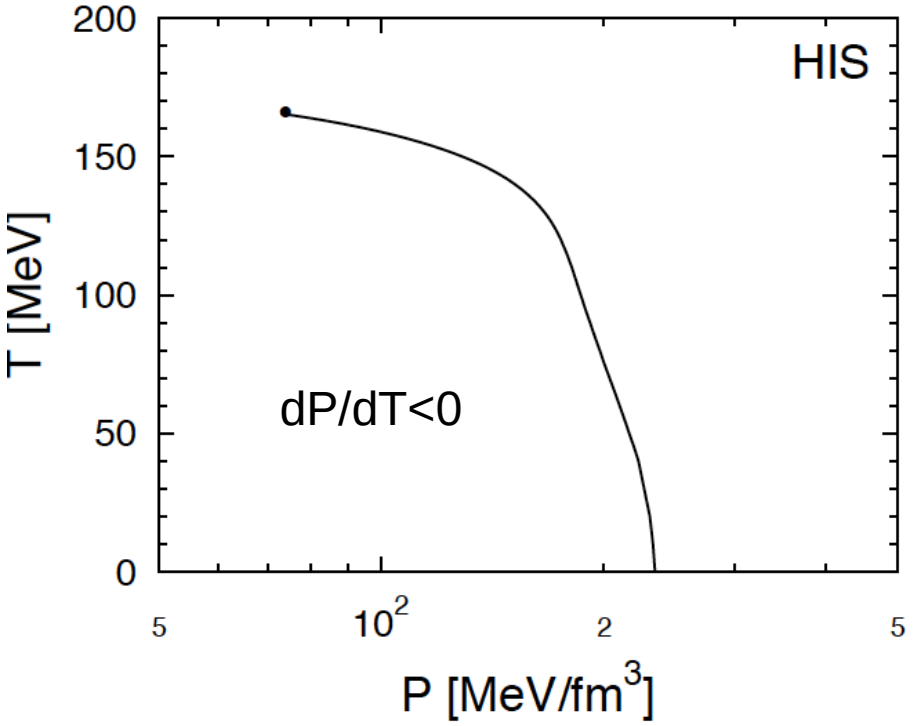


Symmetric Matter:

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



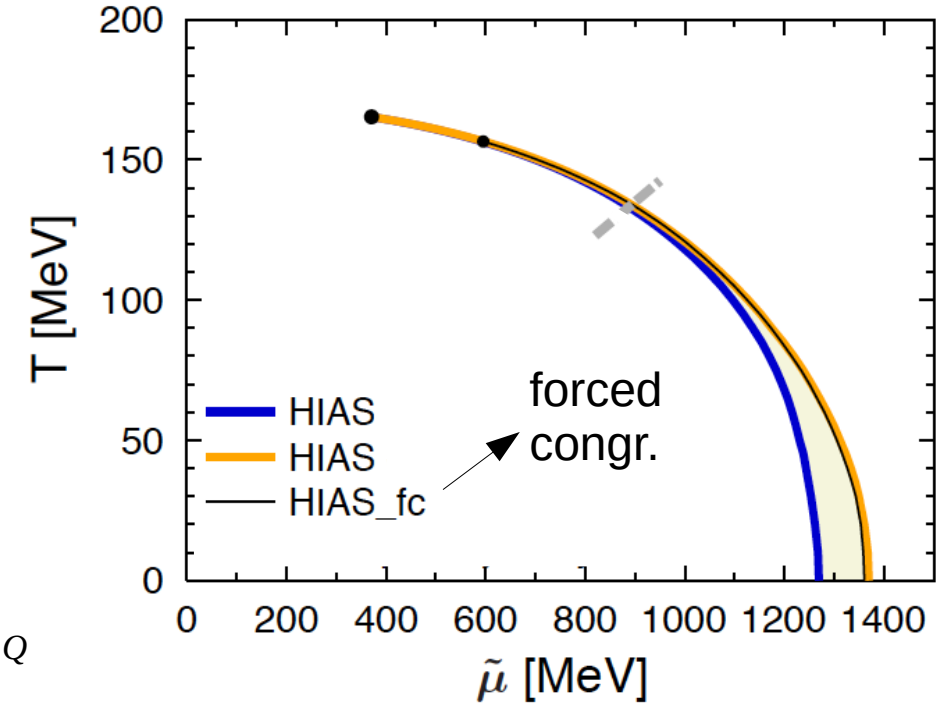


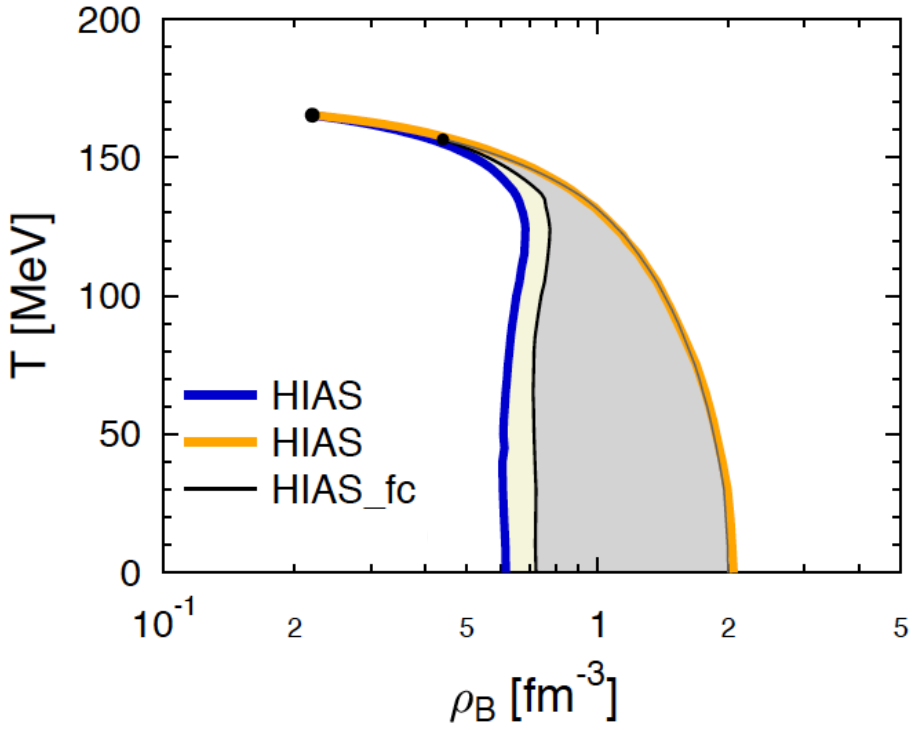


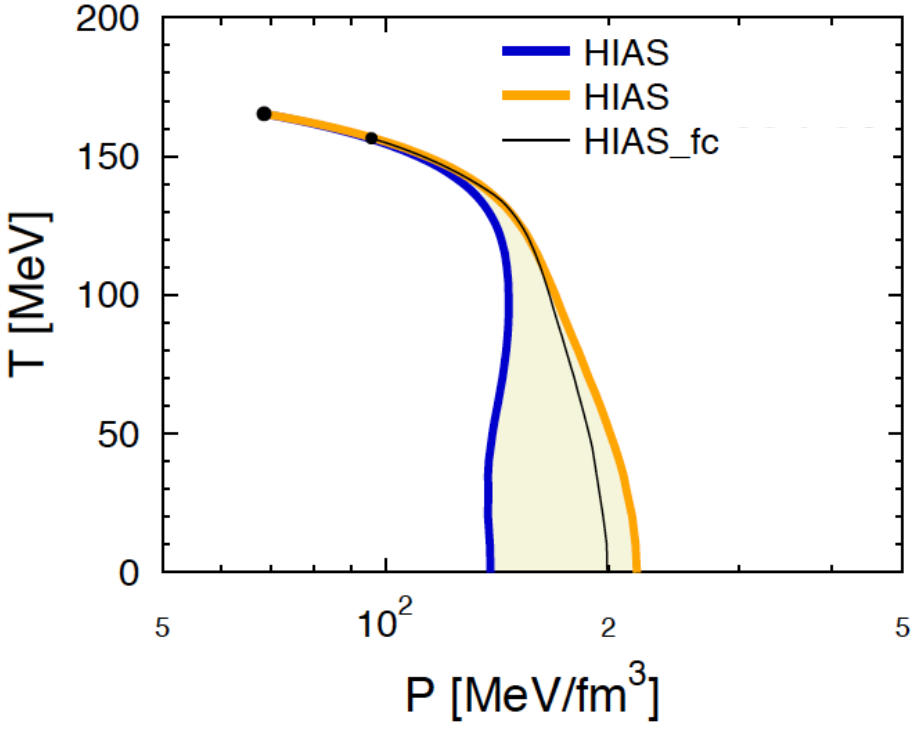
Asymmetric Matter:

- heavy ion collisions with Y_Q=0.3

- more than one conserved charge (baryon #, charge fraction): non-congruent phase transition! $\tilde{\mu} = \mu_B + Y_Q \mu_Q$





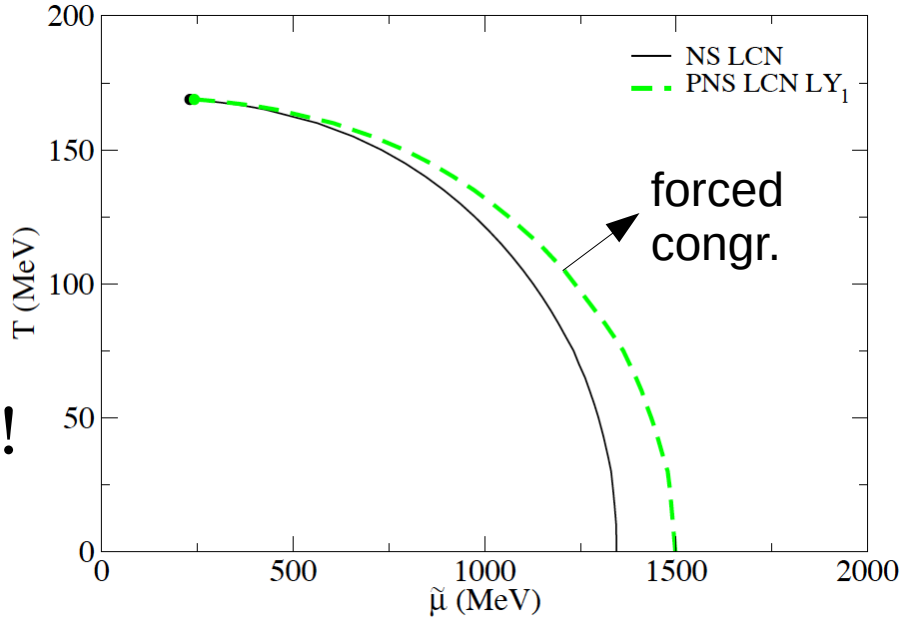


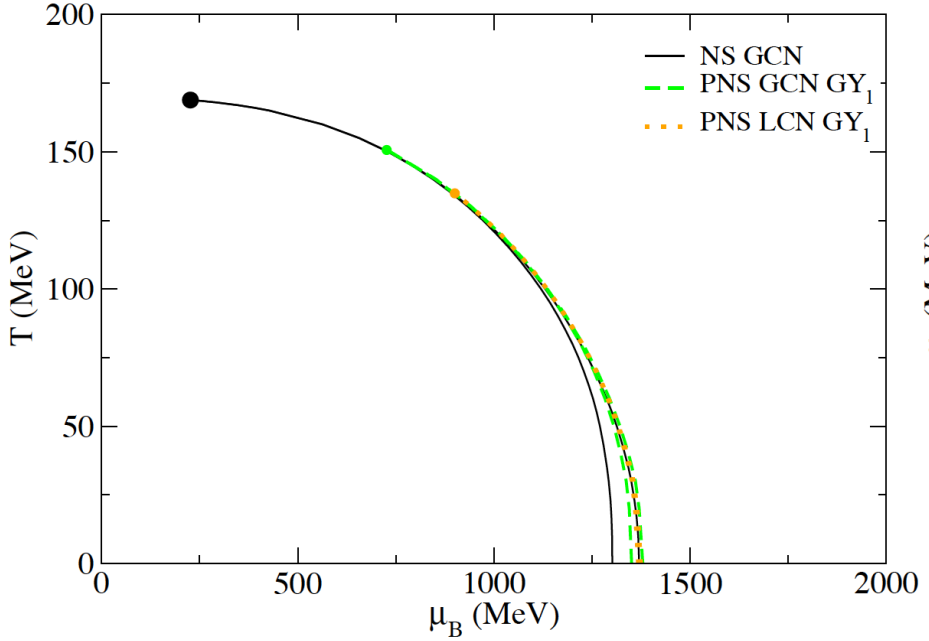
Proto-Neutron-Star Matter:

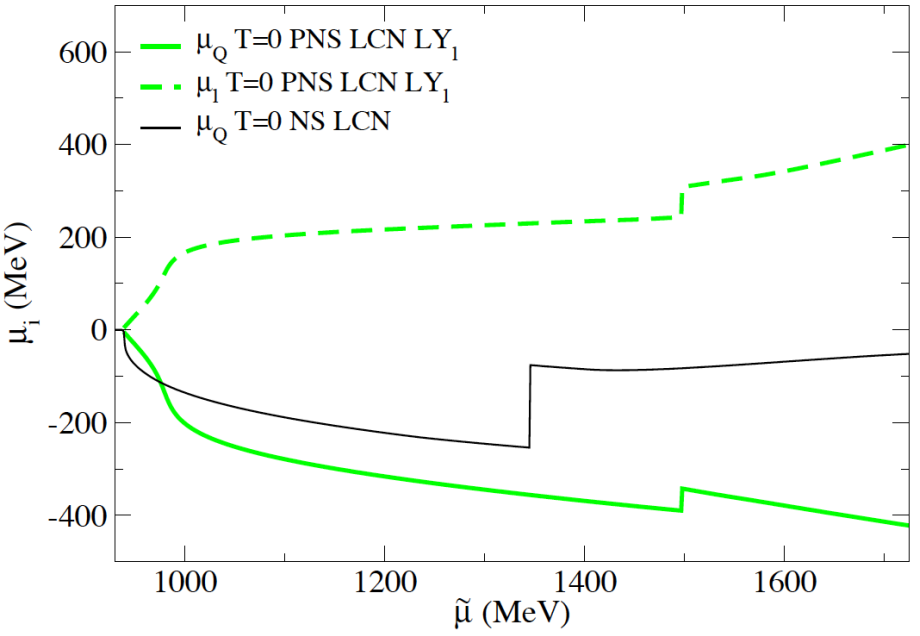
- charge neutral with Y_l=0.4

- more than one conserved charge (baryon #, electric charge, lepton fraction): non-congruent phase transition!

$\tilde{\mu} = \mu_B + Y_l \mu_l$





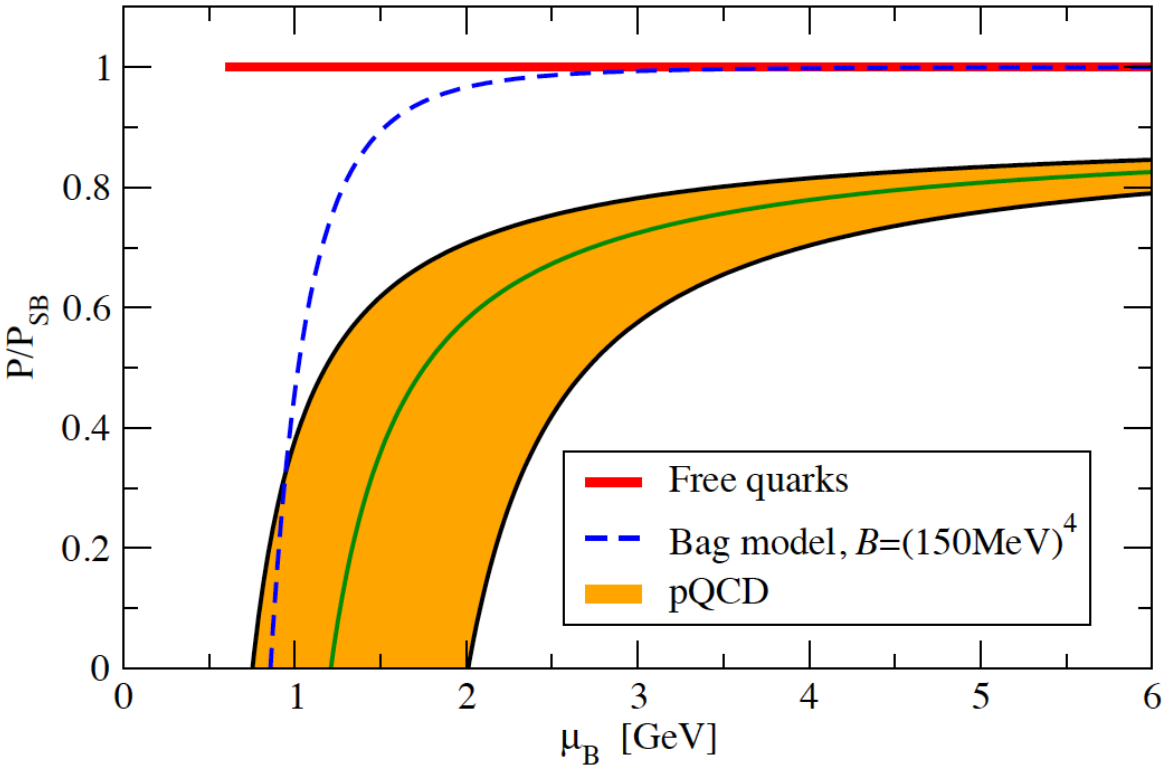


Perturbative QCD:

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

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

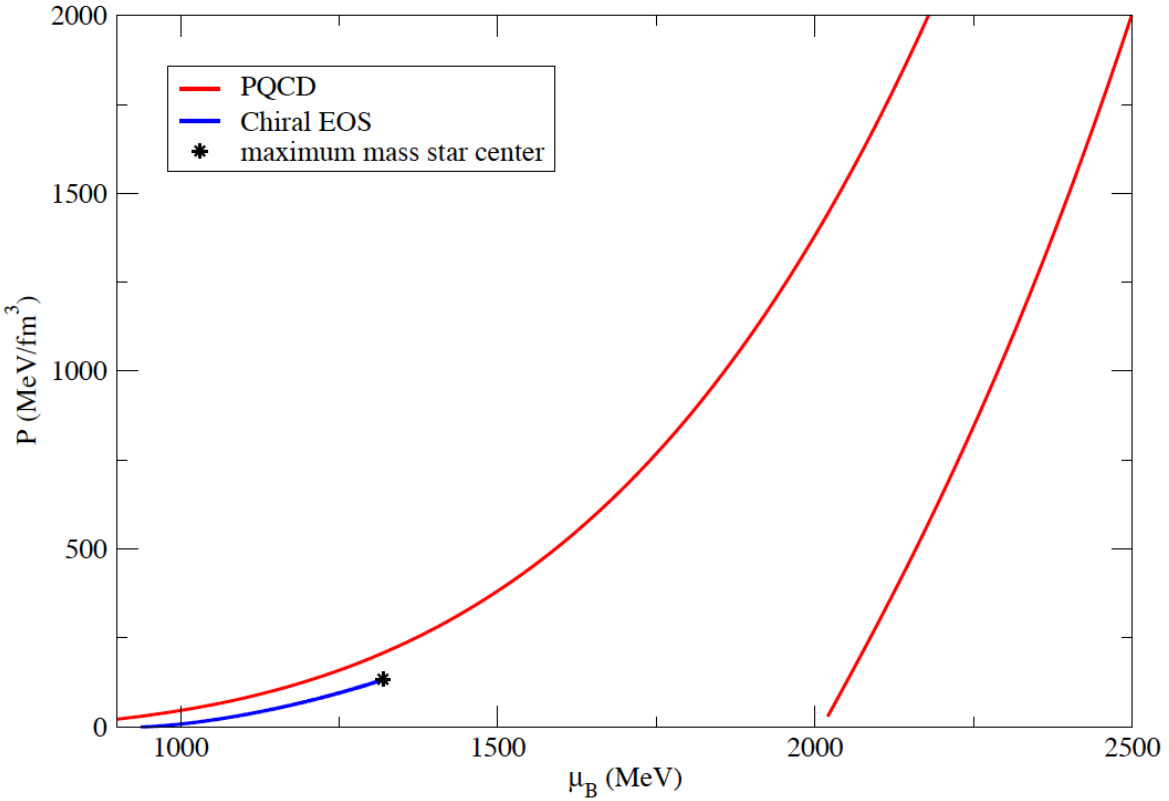
- Bag model failure !



Perturbative limit at T=0

- Chiral EoS until central density of most massive star (~2 M_{Sun})

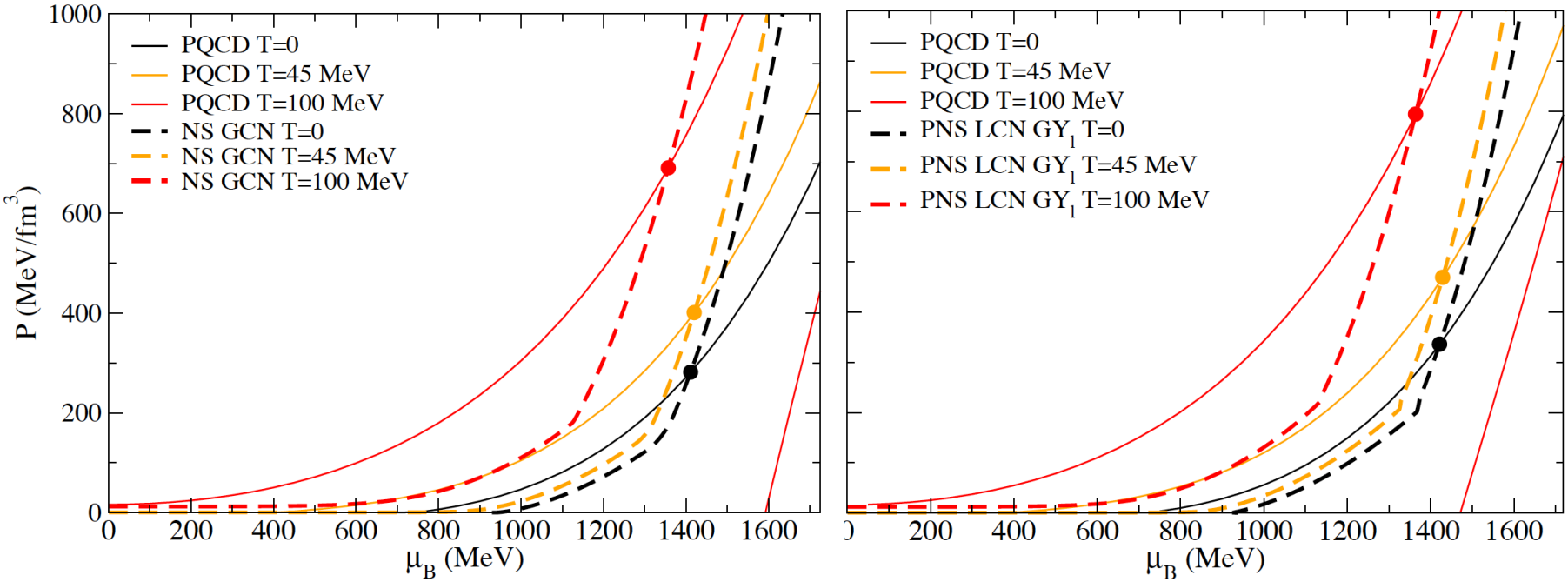
- no vector interactions for quarks



Perturbative limit at finite temperature

- Chiral EoS limits from PQCD

NS	$T = 0$:	$\mu_B = 1411.04$ MeV
	$T = 45$ MeV:	$\mu_B = 1419.76$ MeV
	$T = 100$ MeV:	$\mu_B = 1356.87$ MeV
PNS	$T = 0$:	$\mu_B = 1421.69$ MeV
	$T = 45$ MeV:	$\mu_B = 1429.09$ MeV
	$T = 100$ MeV:	$\mu_B = 1364.08$ MeV



Conclusions and Outlook

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

- better understanding of congruent/non-congruent deconfinement phase transitions: finite temperature description, unified EOS (used for L-G transitions) and that provides particle population

- we already have a 3D star merger hadronic EoS table available online at CompOSE (Publ. Astron. Soc. Aust. 34 (2017) e066)

- we are testing the effects of quarks on star mergers using a 3D table

- we are about to include magnetic field and quark pairing effects