Equation of State Effects on Neutron Star Mergers

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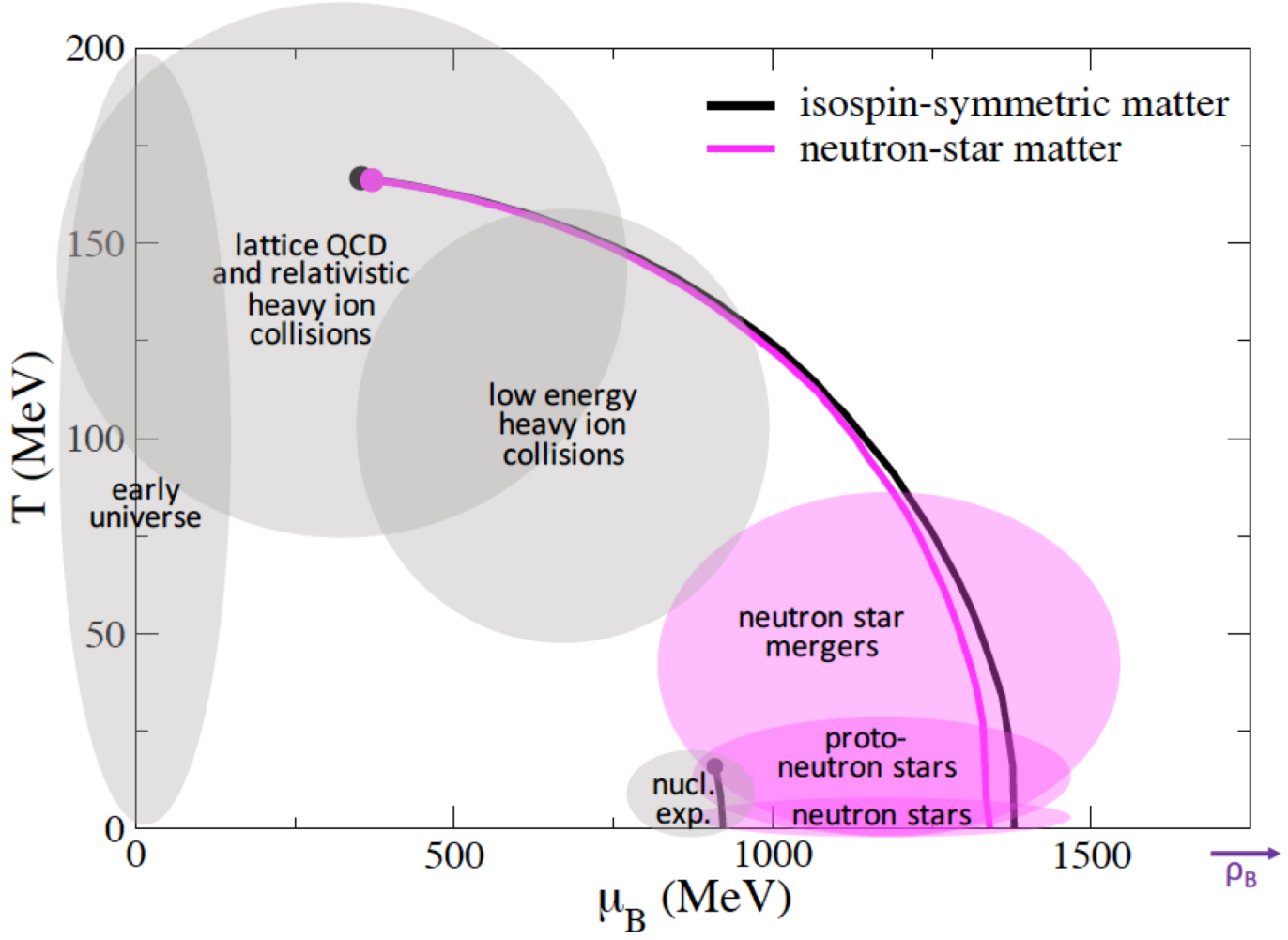
Motivation: QCD Phase Diagram:



- results from CMF model with 1st order phase transition (without mixture of phases)

EoS Ingredients for NS Mergers:

- high density description

- finite/high temperature description

- quantum relativistic description

- description that provides particle population

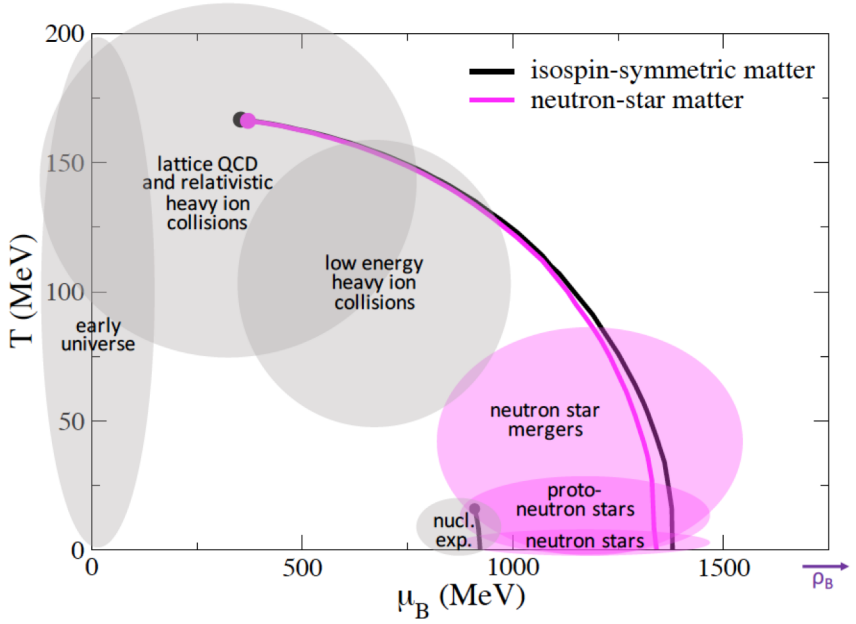
- inclusion of hyperons and quarks

- include chiral symmetry restoration

- in agreement with lattice QCD

- in agreement with heavy-ion collision results

- in agreement with perturbative QCD results



CompOSE (ComStar Online Supernovae Equations of State):

- https://compose.obspm.fr

- online service provides data tables for different state of the art EoS ready for further usage in astrophysical applications, nuclear physics and beyond

- cold NS EoS (1D)

- general purpose EoS (3D)

…

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, heavy ion and astrophysical constraints
- baryon and quark effective masses

$$M_B^* = g_{B\sigma}\sigma + g_{B\delta}\tau_3\delta + g_{B\zeta}\zeta + M_{0_B} + g_{B\Phi}\Phi^2$$
$$M_q^* = g_{q\sigma}\sigma + g_{q\delta}\tau_3\delta + g_{q\zeta}\zeta + M_{0_q} + g_{q\Phi}(1-\Phi)$$

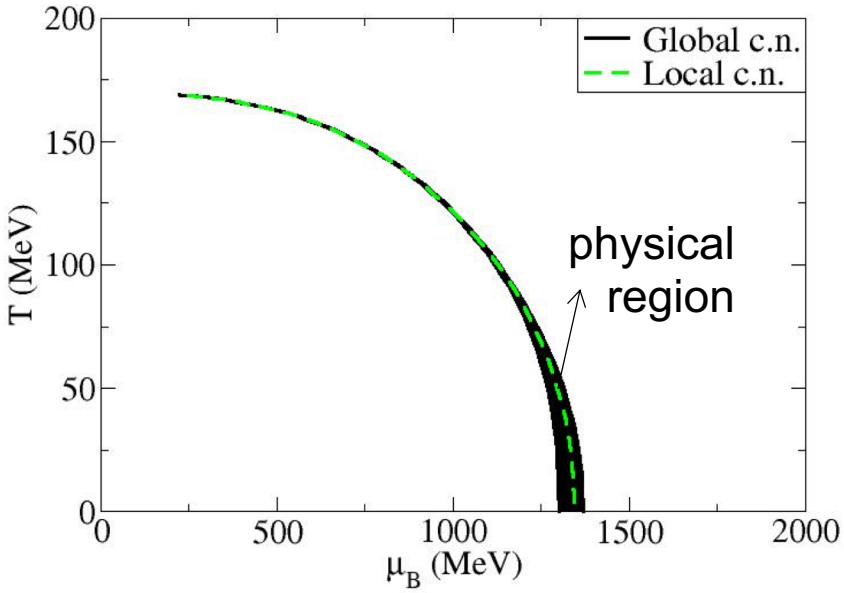
- 1st order phase transitions or crossovers (order parameters **σ**, **Φ**)
- potential for **Φ** (deconfinement)

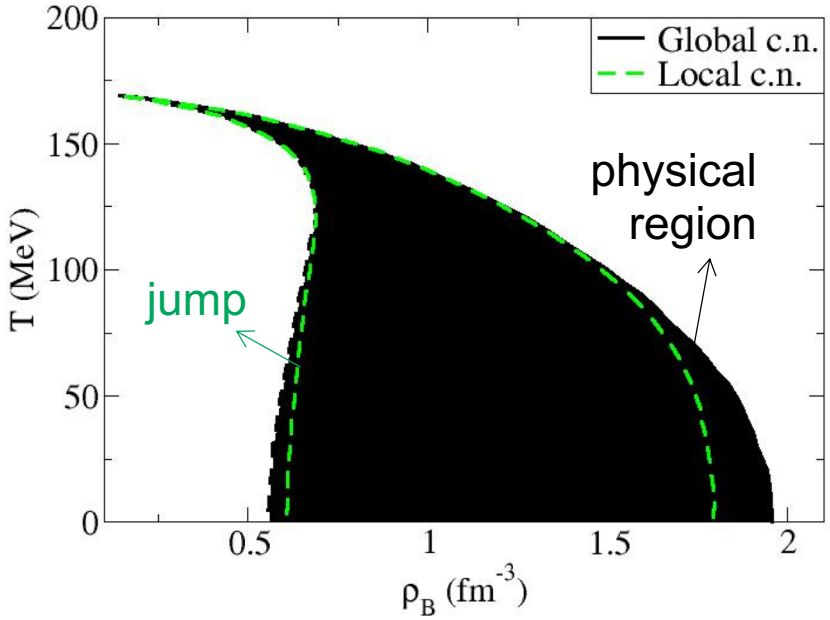
$$U = (a_o T^4 + a_1\mu_B^4 + a_2 T^2\mu_B^2)\Phi^2 + a_3 T_o^4 \ln(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4)$$

Neutron Star Matter: Local vs Global Charge Neutrality

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

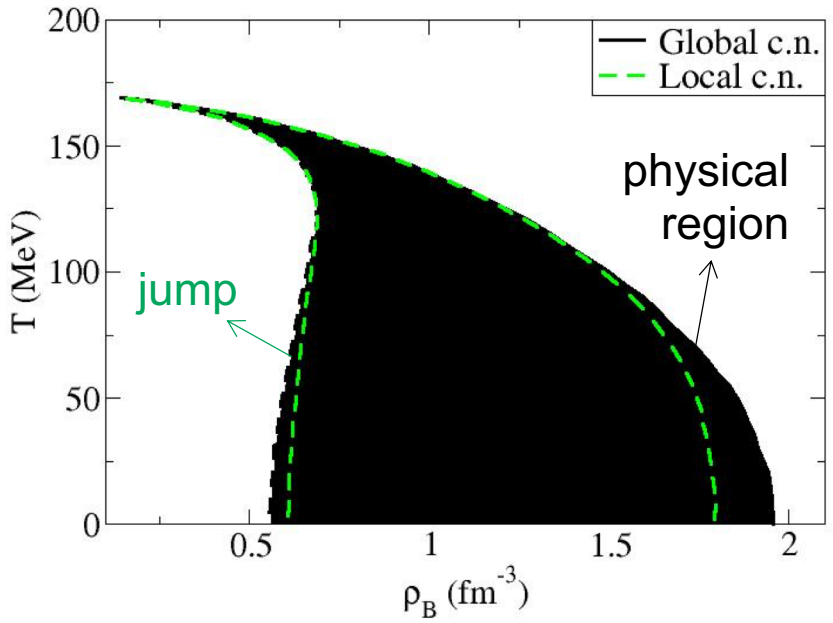
- "mixed" quantities like baryon number density $\rho_B = \lambda\rho_B^Q + (1-\lambda)\rho_B^H$

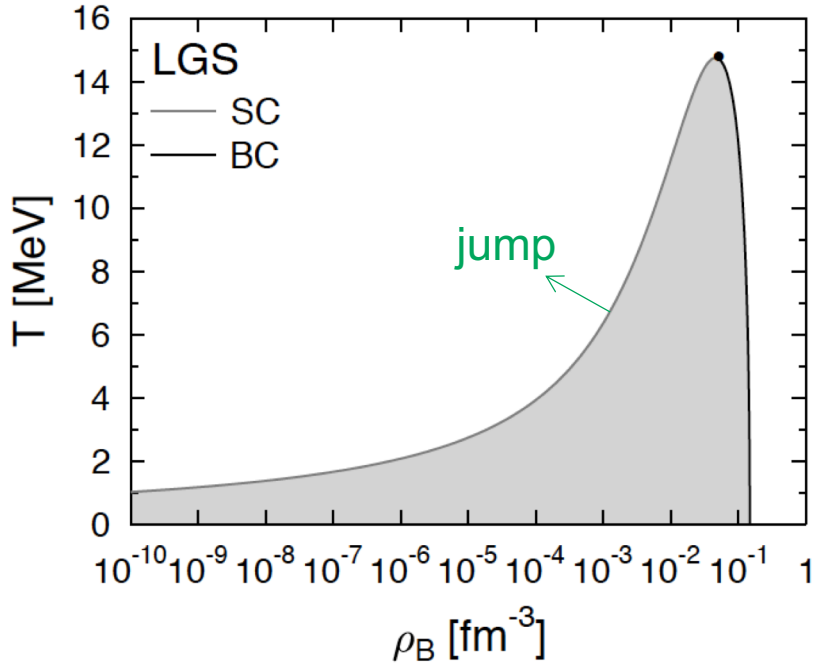




Non-congruent Phase Transitions:

- more than one globally conserved charge within 2 macroscopic phases within a Coulomb-less model: baryon #, electric charge
- local concentration of charges vary during phase transition
- same chemical potential (assoc. to charge) in both phases (μ_q)
- very different from symmetric matter liquid-gas (LGS)

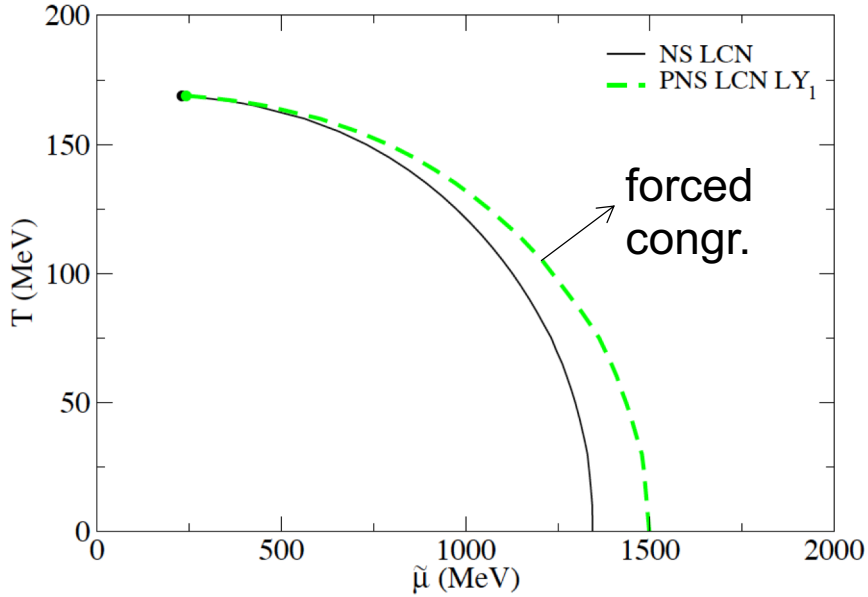


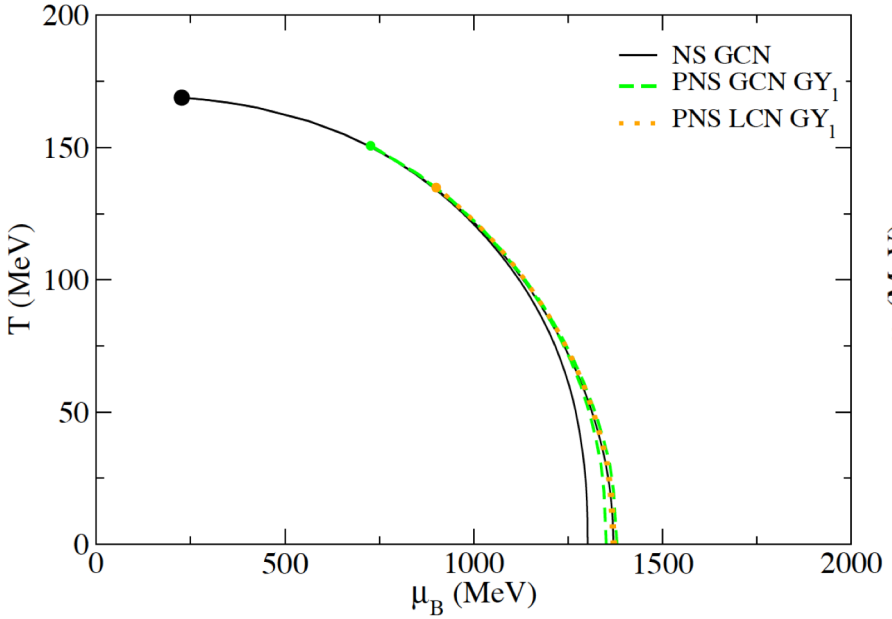


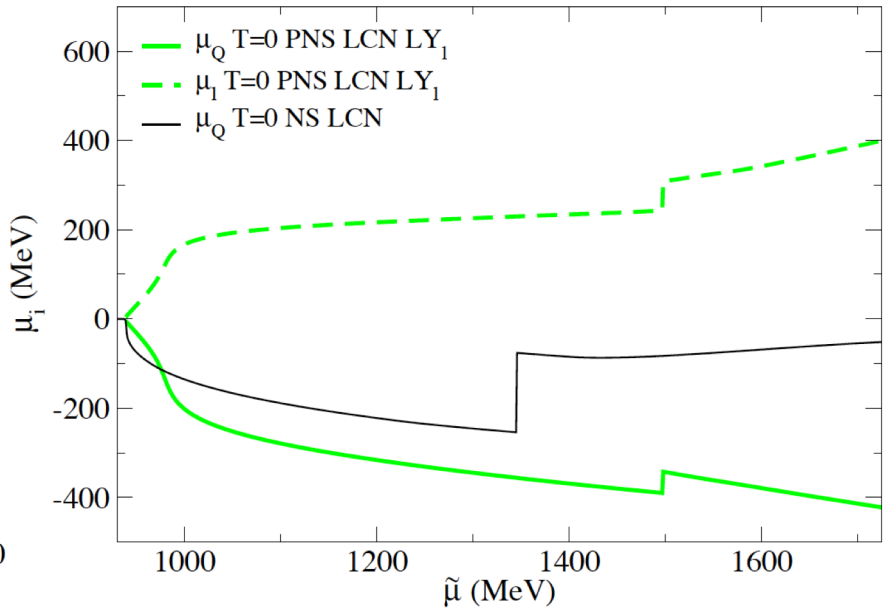
Proto-Neutron-Star Matter:

- charge neutral with Y_l=0.4
- more than one conserved charge (baryon #, electric charge, lepton fraction): non-congruent phase transition!

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





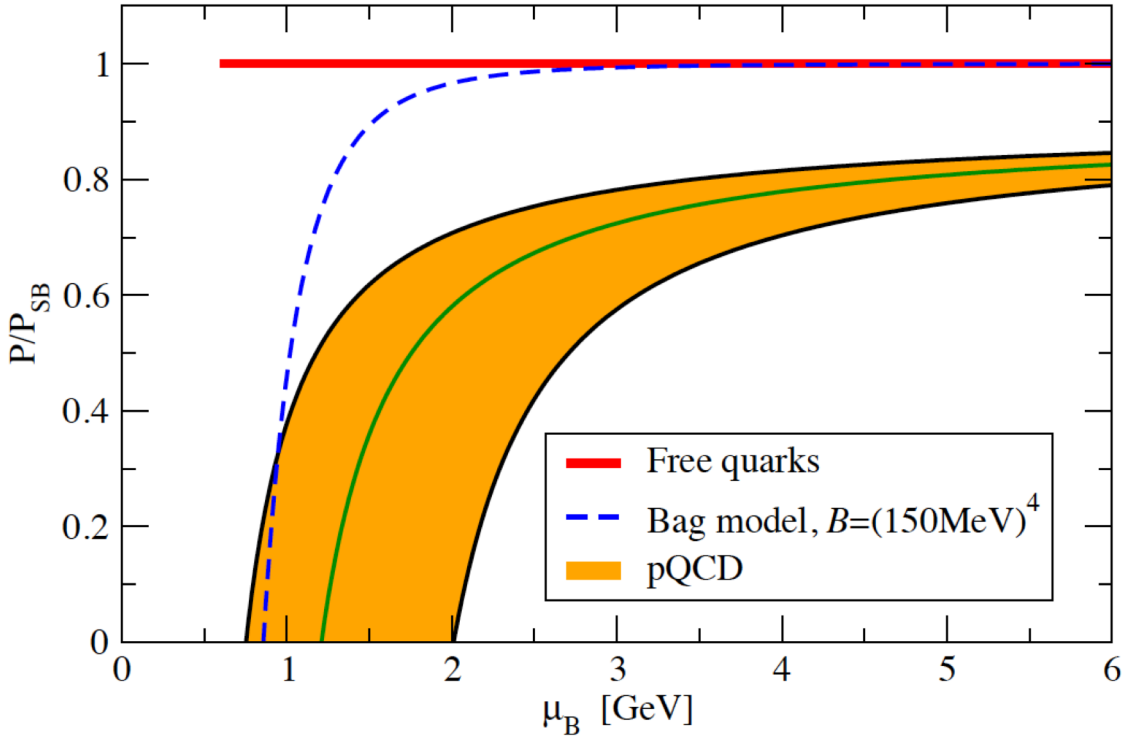


Perturbative QCD:

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

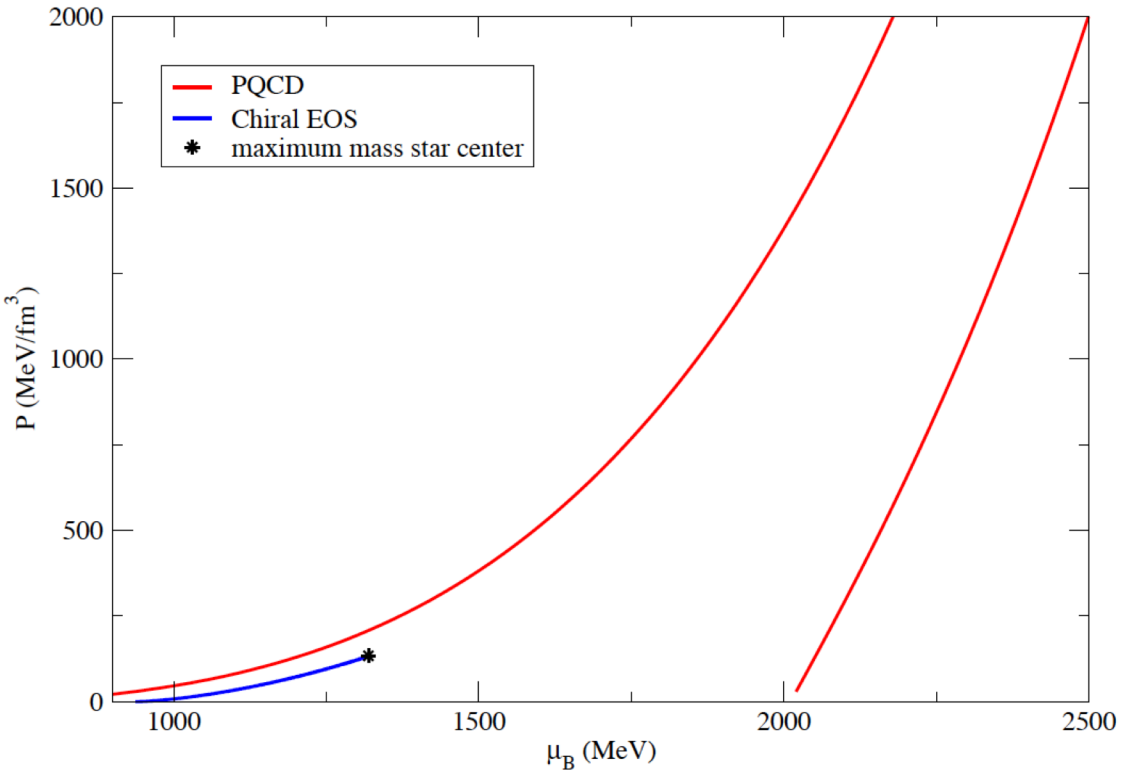
- 3-flavor QGP at zero temperature including β-equilibrium and charge neutrality

- Bag model failure !



Perturbative limit at T=0:

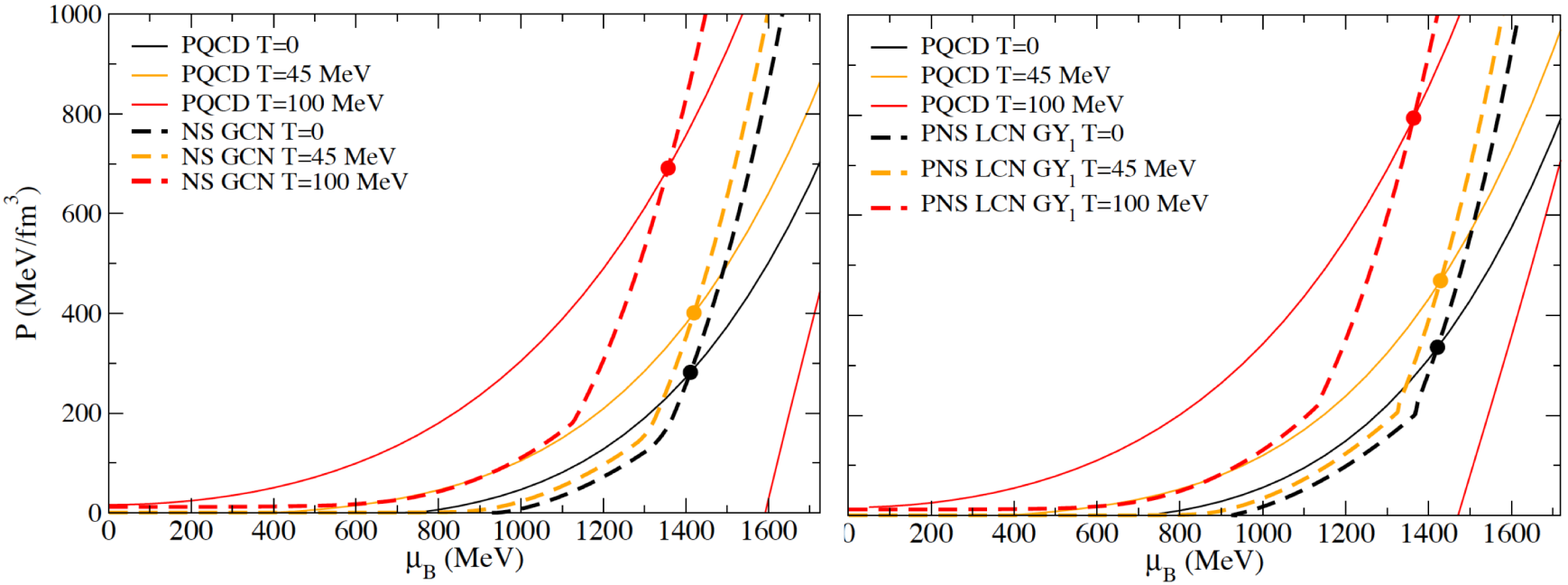
- Chiral EoS until central density of most massive star (~2 M_{Sun})
- no vector interactions for quarks



Perturbative limit at finite temperature:

- CMF 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

- better understanding of congruent/non-congruent deconfinement phase transitions with unified EOS (used for L-G transitions)

- signature for 1st order phase transition from astrophysics?

- need of more realistic EoS's (that have been compared with PQCD)

- 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

Preliminary NS merger results

- CMF EoS
- 2 low-mass stars (without quarks)