Neutron stars and hot QCD from unified equation of state

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Chiral SU(3)-flavor parity-doublet Polyakov-loop quark-hadron mean-field model, CMF

SU(3) — baryon octet interacts through mesonic fields: scalar σ and ζ, vector ω, φ, and ρ:

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -2\frac{\Lambda}{\sqrt{6}} \end{pmatrix}$$

$$\mathcal{L}_B = \sum_i (\bar{B}_i i \partial\!\!\!/ B_i) + \sum_i (\bar{B}_i m_i^* B_i) + \sum_i \left(\bar{B}_i \gamma_\mu (g_{\omega i}\omega^\mu + g_{\rho i}\rho^\mu + g_{\phi i}\phi^\mu) B_i\right)$$

Parity doublet — baryon octet is doubled by parity partners with same quantum numbers but opposite parity and higher masses. Masses are dynamically generated by chiral fields σ and ζ:

$$m^*_{i\pm} = \sqrt{\left[(g^{(1)}_{\sigma i}\sigma + g^{(1)}_{\zeta i}\zeta)^2 + (m_0 + n_s m_s)^2\right]} \pm (g^{(2)}_{\sigma i}\sigma + g^{(2)}_{\zeta i}\zeta)$$

Quark-hadron — realization of the deconfinement within PNJL-like approach. Quarks have dynamical masses controlled by chiral fields:

$$m_q^* = -g_{q\sigma}\sigma + \delta m_q + m_{0q}$$
$$m_s^* = -g_{s\zeta}\zeta + \delta m_s + m_{0q}$$

quark deconfinement is driven by Polyakov loop order parameter Φ:

$$P_q = \sum_{i \in Q} d_i \int \frac{d^3k}{(2\pi)^3} \frac{k^4}{E_i^*} \left[\frac{1}{\frac{1}{\Phi} e^{-(E_i^* - \mu_i^*)/T} + 1} + \frac{1}{\frac{1}{\Phi^*} e^{-(E_i^* + \mu_i^*)/T} + 1} \right]$$

that is controlled by potential U(Φ):

$$U = -\frac{1}{2}(a_0 T^4 + a_1 T_0 T^3 + a_2 T_0^2 T^2)\Phi\Phi^* + b_3 T_0^4 \log[1 - 6\Phi\Phi^* + 4(\Phi^3 + \Phi^{*3}) - 3(\Phi\Phi^*)^2]$$

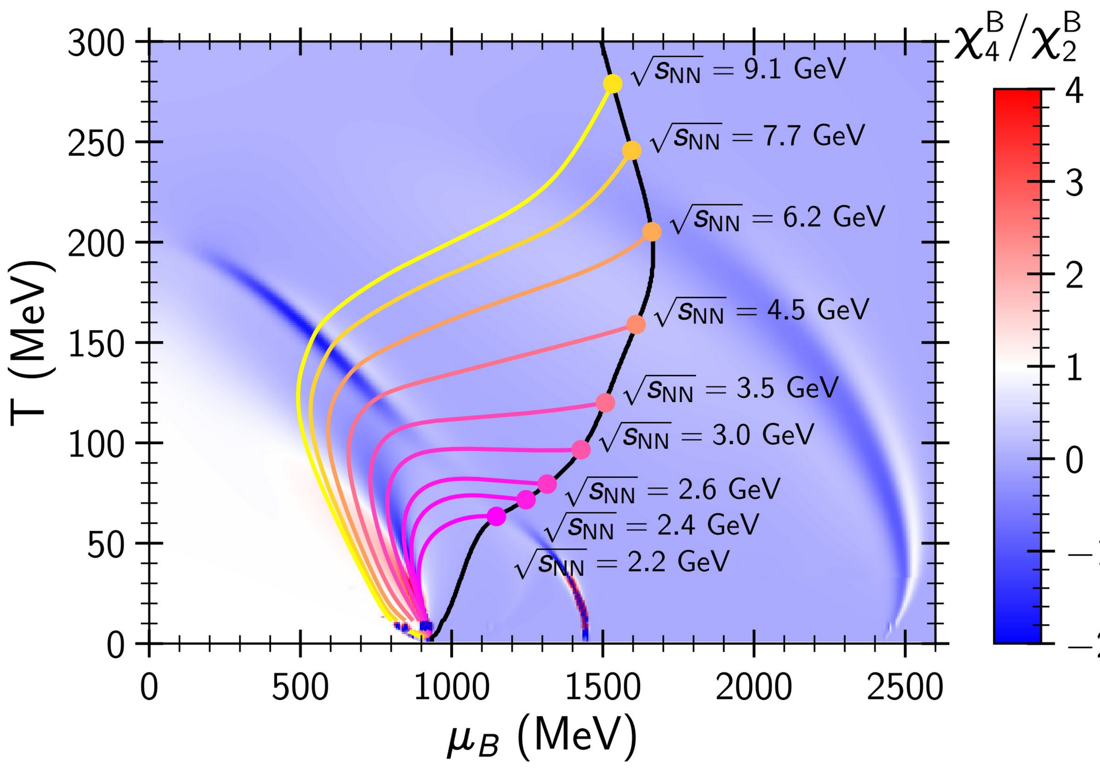
Hadron-resonance gas is included with **excluded-volume** corrections to mimic hard-core repulsion:

$$\rho_j = \frac{\rho_j^{id}(T, \mu_j^* - v_j p)}{1 + \sum_i^{HRG} v_i \rho_i^{id}(T, \mu_i^* - v_i p)}$$

for baryons v_B=1 fm^{-3}, for mesons v_M=1/8 fm^{-3}, and quarks are point-like v_q= 0.

These ingredients include main features of QCD phenomenology, so the CMF model [1-3] is applicable for modeling QCD thermodynamics from low to high temperatures and densities.

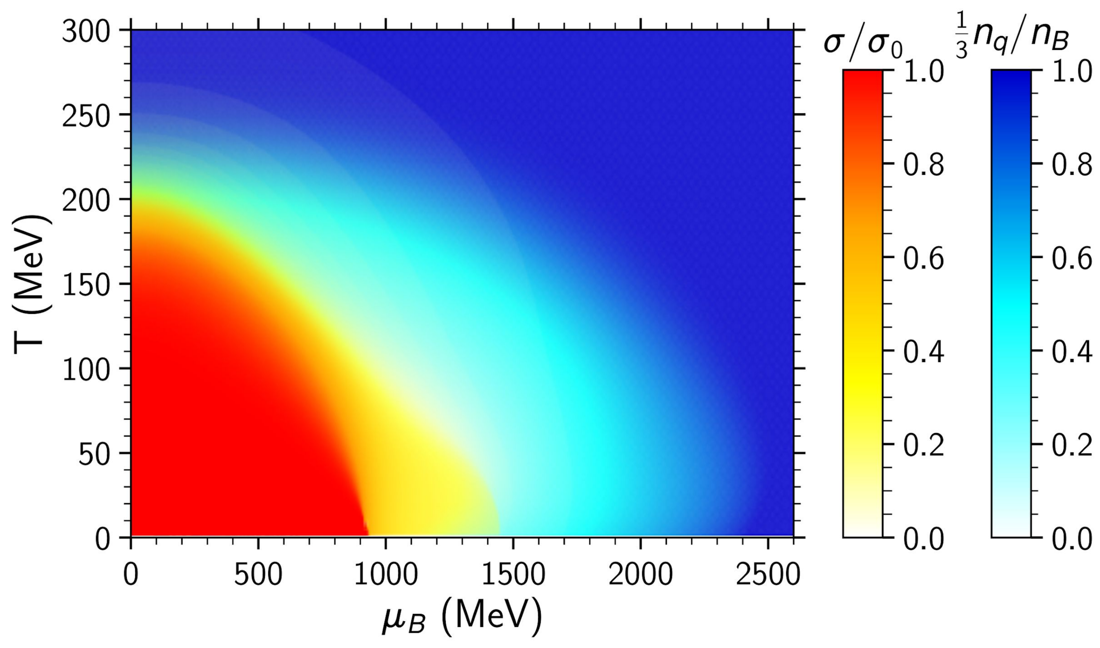
PHASE DIAGRAM



Lines of constant entropy per baryon, S/A, illustrate 1D hydro simulations of heavy ion collisions. Values of S/A are related to collision energy by shock solution, the Relativistic Rankine Hugoniot Taub adiabat.

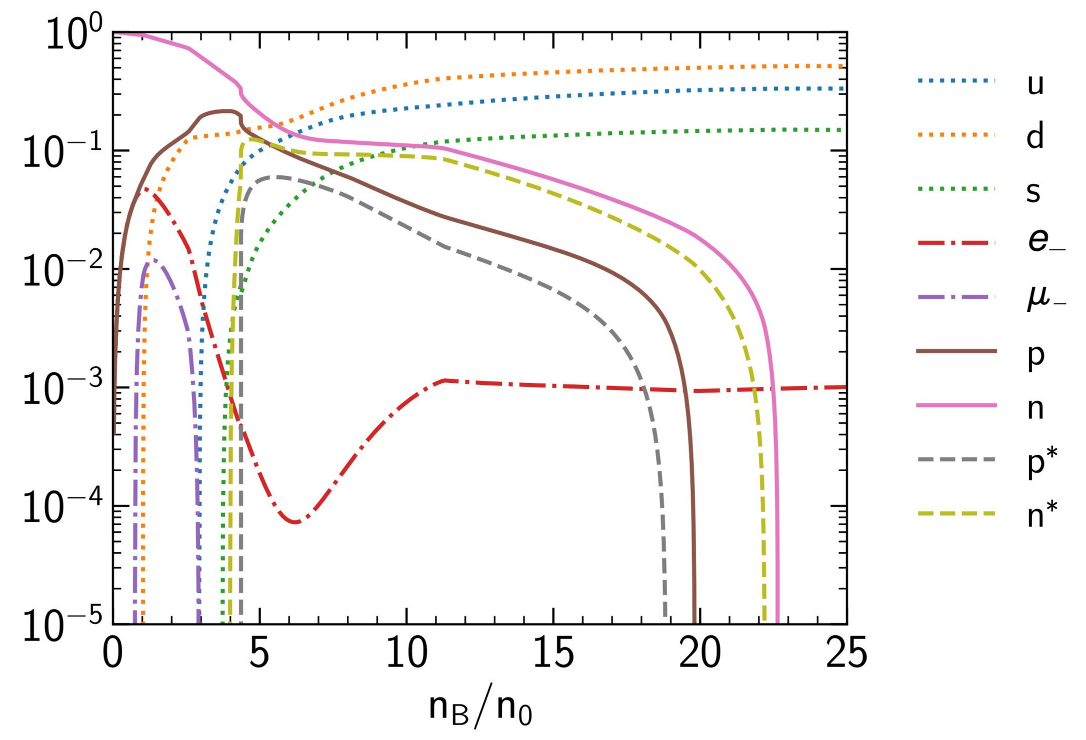
Kurtosis, χ_4^B/χ_2^B, indicates three critical regions:

- Nuclear liquid-vapor phase transition at μ_B≈940 MeV and T < 20 MeV with critical endpoint T^{CP}≈20 MeV. Remnants are visible at μ_B=0 and T > 100 MeV [7].
- Chiral symmetry restoration. Associated phase transition occurs at μ_B≈1400 MeV and T < 20 MeV, T^{CP}≈20 MeV. Mass symmetry between parity partners is restored, as well as quark masses are decreased. Significant quark fraction start to appear.
- Transition to quark matter, all baryon density is generated by deconfined quarks, ⅓ n_q/n_B=1. Is always of second order and take place at very large densities n_B≳20n_0.

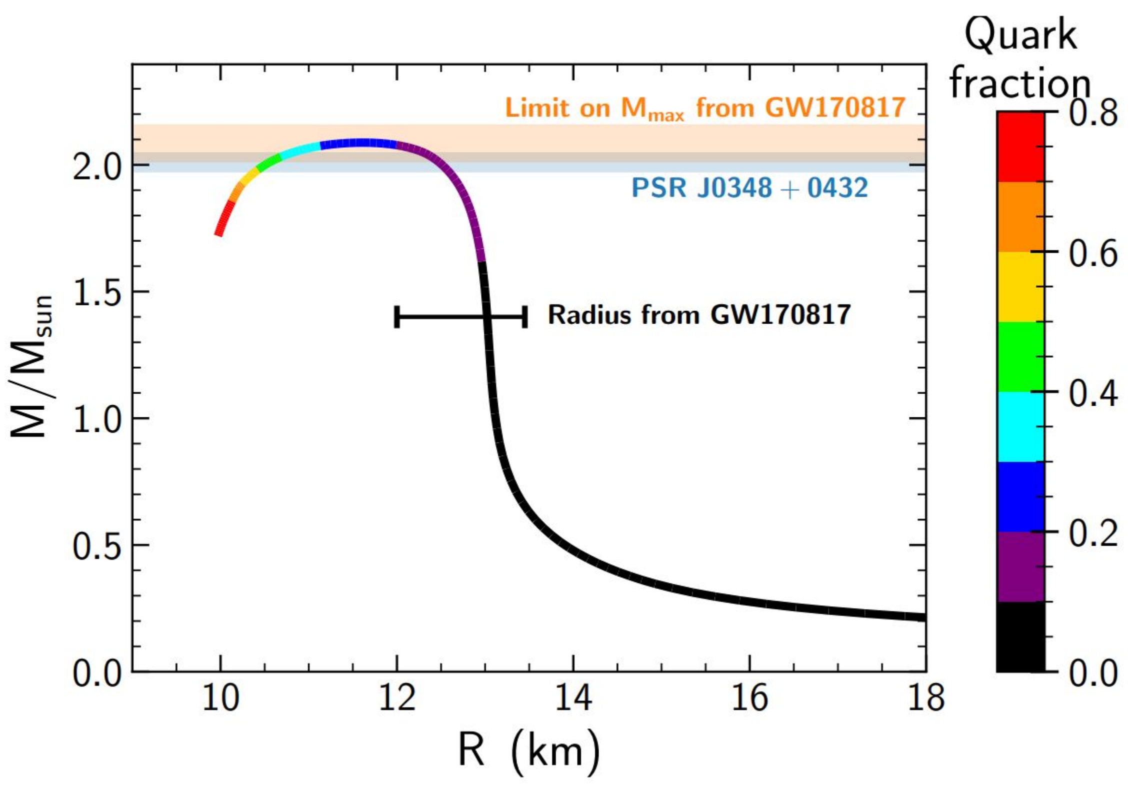


Quarks start to appear only after chiral symmetry is restored. Quarks are in mixture with hadrons. Only later the quark matter, ⅓ n_q/n_B=1, appears.

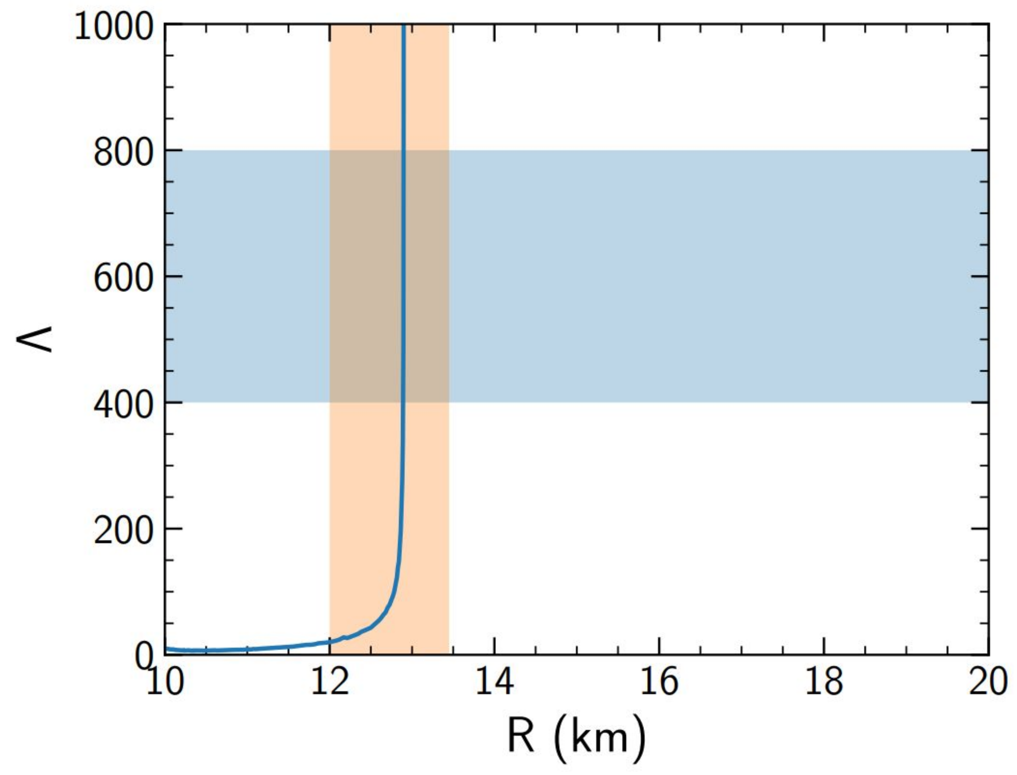
NEUTRON STAR PROPERTIES



Particle content of neutron stars in CMF model. Presented are ratios of particle density to the baryon density n_i/n_B at T = 0 in β -equilibrium, for quarks a factor of 1/3 is used. Are presented as functions of baryon density n_B.

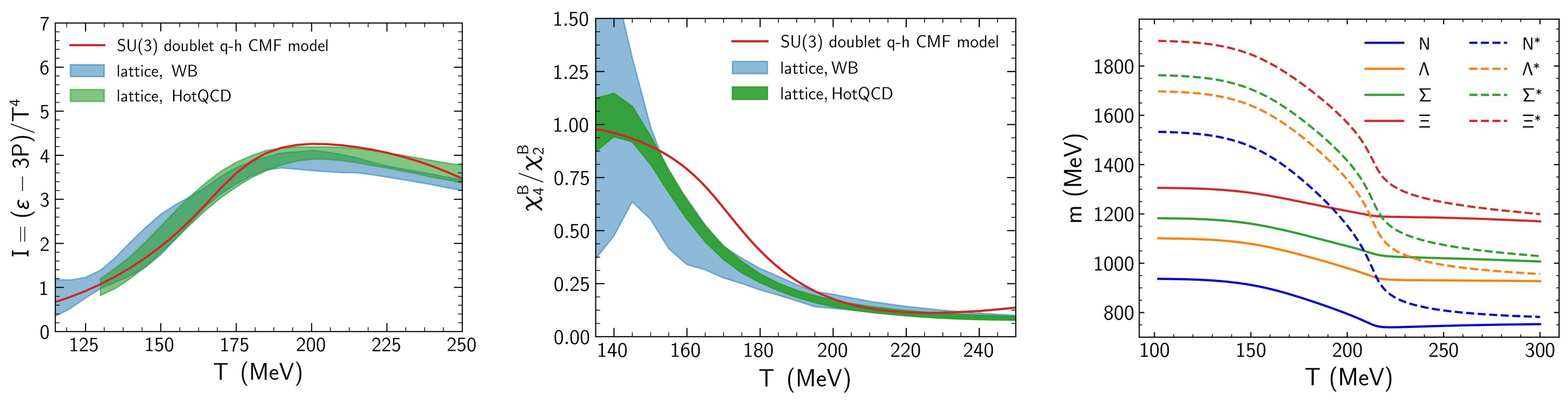


Mass-radius diagram is in agreement with astrophysical observations. Stars up to 2.1 M_{sun} are supported [8]. Stable stars contain <30% of deconfined quarks. At high central densities $n_{central}$> 6n_0 stars become unstable, as a result stars with significant quark content are disfavored.



Dimensionless tidal deformability Λ — measures stars' induced quadruple moment as a response to the external tidal field. Important quantity during inspiral phase of NS merger when tidal forces are large. Bands — recent constraints for radius and tidal deformability of 1.4 M_{sun} star [9].

CMF at μ_B=0: lattice QCD and parity doubling



In the CMF model the parameters of PNJL sector are modified in accord with lattice QCD [4,5] data. Interaction measure *I* was fitted by modifying parameters of the Polyakov loop potential U(Φ): T_0, a_1, a_2, b_3 and quark couplings to chiral fields $g_{q\sigma}$, $g_{q\zeta}$ [1]. Kurtosis, χ_4^B/χ_2^B, at μ_B=0 is the CMF model prediction.
At μ_B=0 masses of octet baryons and respective parity partners smoothly decrease, so at hight *T* mass degeneracy among parity partners is restored. The behavior is similar to recently observed in lattice QCD [6].

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SUMMARY

- Chiral SU(3) parity-doublet Polyakov loop quark-hadron mean-field model — is a unified phenomenological approach to model QCD thermodynamics at wide range of scales;
- μ_B=0 lattice QCD data is used to constrain parameters of model's quark sector;
- Nuclear liquid-vapor phase transition gives strong signals in fluctuations even at μ_B=0;
- Chiral symmetry restoration and transition to quark matter phase are at very high μ_B and/or T;
- The CMF neutron stars are in agreement with current astrophysical constraints;
- Transition to quark matter is second order and at high densities n_B≳20n_0.