QCD thermodynamics from SU(3) parity-doublet quark-hadron chiral model

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MODEL DESCRIPTION

SU(3) parity-doublet quark-hadron chiral model is a consistent approach to describe QCD statistical and thermodynamical properties on different scales [1,2].

Main ingredients of the model:

- Mean field approximation: $\hat{A} \to \langle A \rangle$
- Baryons of SU(3) octet interact via scalar (σ,ζ) and vector (ω, ρ, φ) mesons within non-linear sigma model:

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

- Symmetry among parity partners is restored at finite μ_B where scalar fields vanish:

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

- σ, ζ drive chiral symmetry breaking with the following potential V:

$$V = V_0 + \frac{1}{2}k_0(\sigma^2+\zeta^2) - k_1(\sigma^2+\zeta^2)^2 + k_2(\sigma^4/2+\zeta^4) + k_6(\sigma^6+4\zeta^6)$$

- Quarks contribute to grand canonical potential within PNJL-type description with Polyakov loop $\mathbf{\Phi}$ as an order parameter for deconfinement:

$$\Omega_q = -T\sum_{i\in Q}\frac{\gamma_i}{(2\pi)^3}\int d^3k \ln\left(1+\Phi\exp\frac{E_i^*-\mu_i}{T}\right)$$

where mean fields generate effective masses:

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

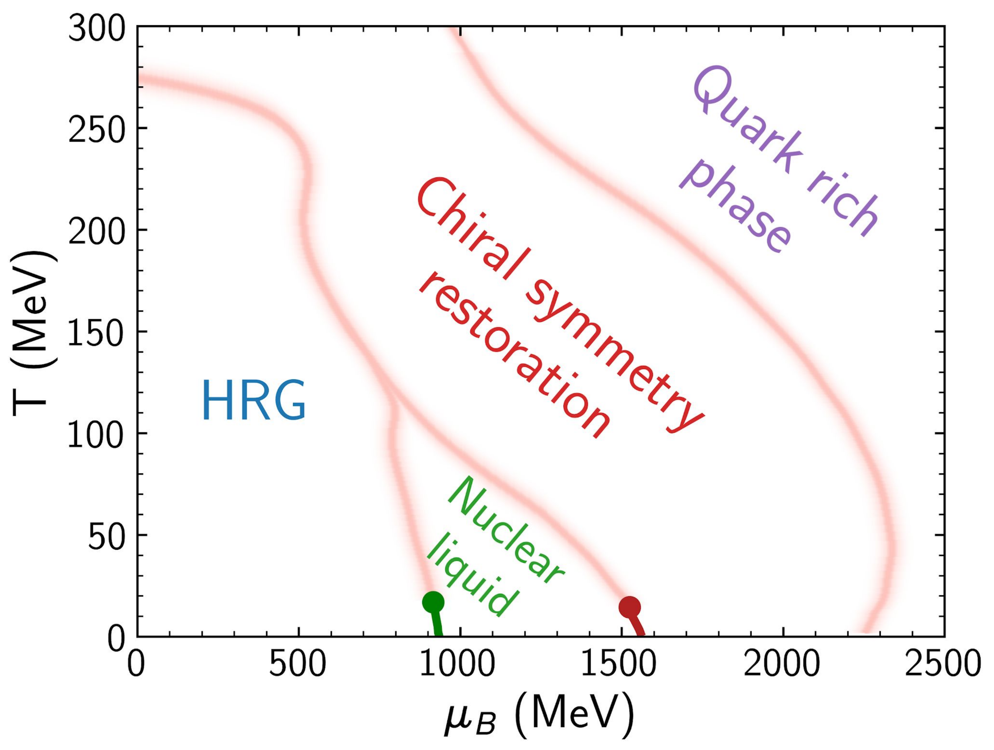
and dynamics of $\mathbf{\Phi}$ are controlled by effective potential U:

$$U = -\frac{1}{2}a(T)\Phi\Phi^* + b(T)\log[1-6\Phi\Phi^* + 4(\Phi^3+\Phi^{*3}) - 3(\Phi\Phi^*)^2],$$
$$a\ (T) = a_0T^4 + a_1T_0T^3 + a_2T_0^2T^2, \quad b(T) = b_3T_0^3T$$

- **plus** PDG list of hadrons with **excluded volume** corrections for both baryons and mesons:

$$\rho_i = \frac{\rho_i^{\mathrm{id}}}{1+\sum_j v_j\rho_j^{\mathrm{id}}}$$

PHASE DIAGRAM



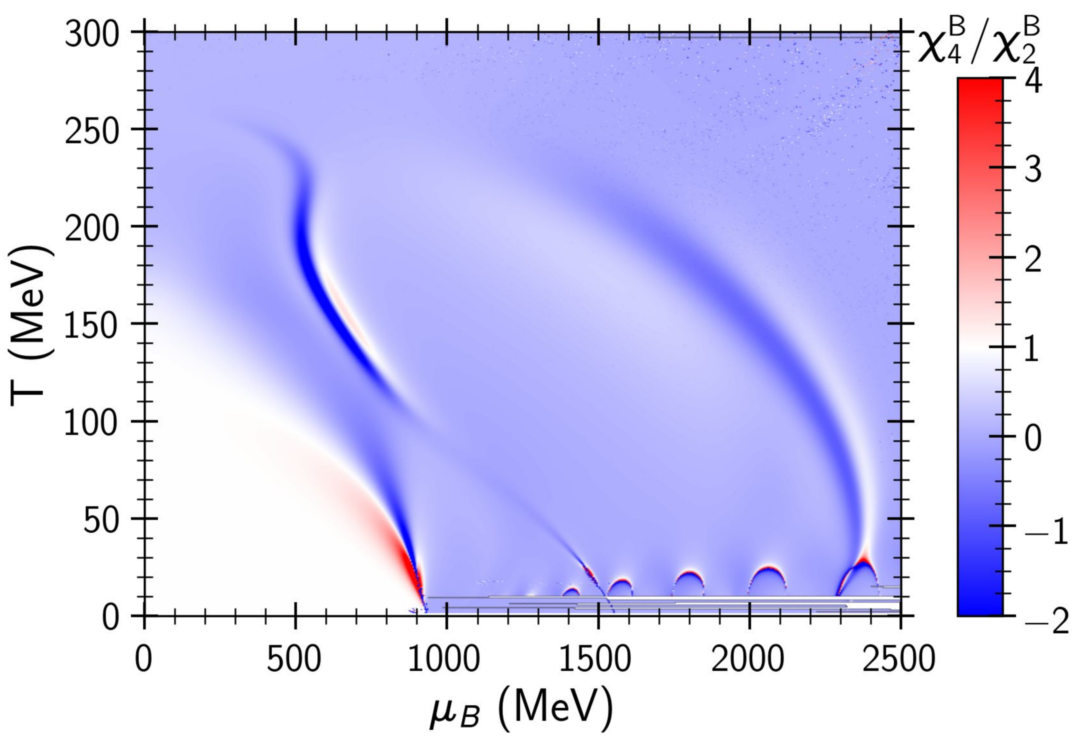
Two low-temperature critical points associated with:

- **nuclear liquid-gas phase transition**;
- **chiral symmetry restoration**.

At T>20 MeV transitions between phases are driven by **smooth crossovers** (red lines in plot).

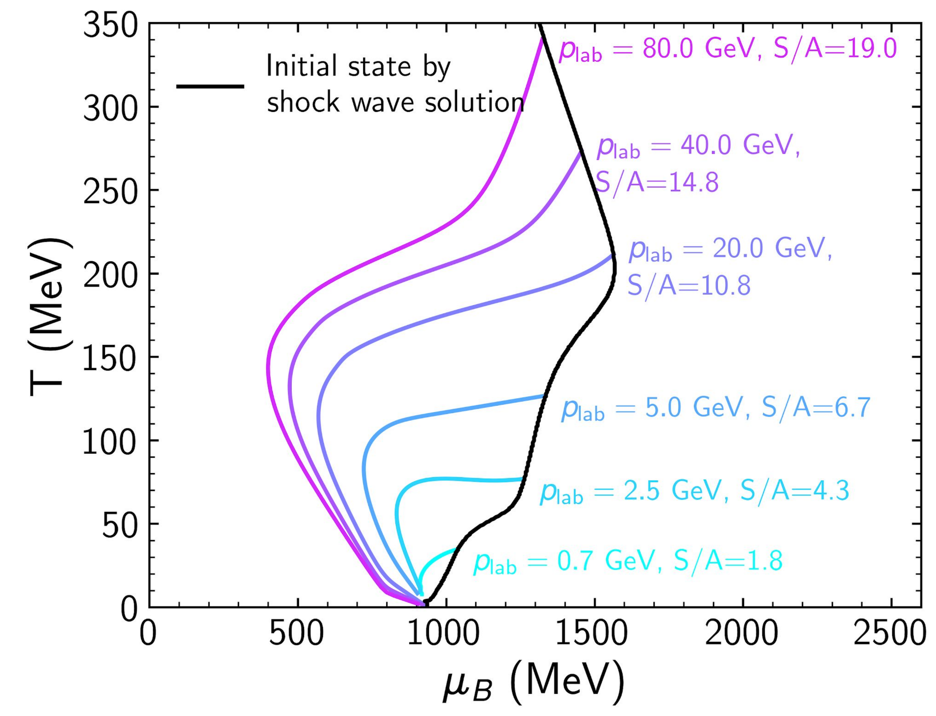
At high values of μ_B there is a crossover transition to **quark rich phase** with $n_q/n_B \to 1$ where $\mathbf{\Phi} \to 1$.

BARYON KURTOSIS STRUCTURE



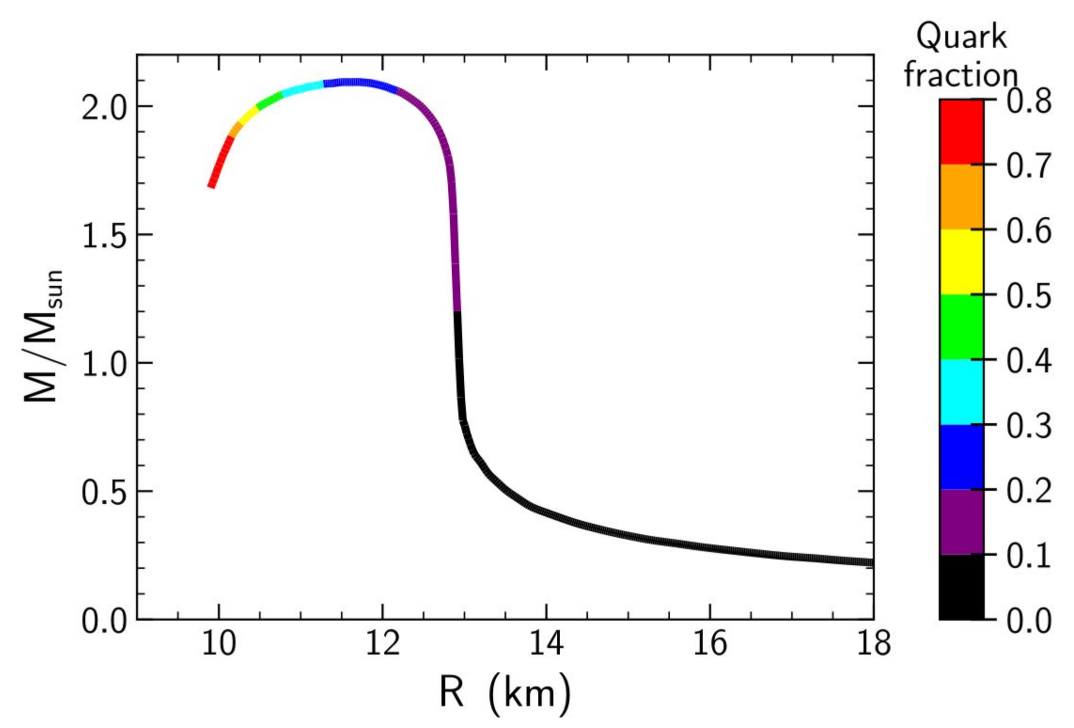
- At experimentally accessible region (*i.e. for weakly interacting hadron-resonance gas*) deviations from baseline are driven by **remnants of nuclear liquid-gas phase transition** [5].
- Same for crossover at μ_B=0: behavior of χ^B_4/χ^B_2 at crossover region is mainly driven by **remnants of nuclear liquid-gas phase transition.**
- Effects from chiral symmetry restoration and transition to quark-dominated phase **are far away in T and μ_B.**

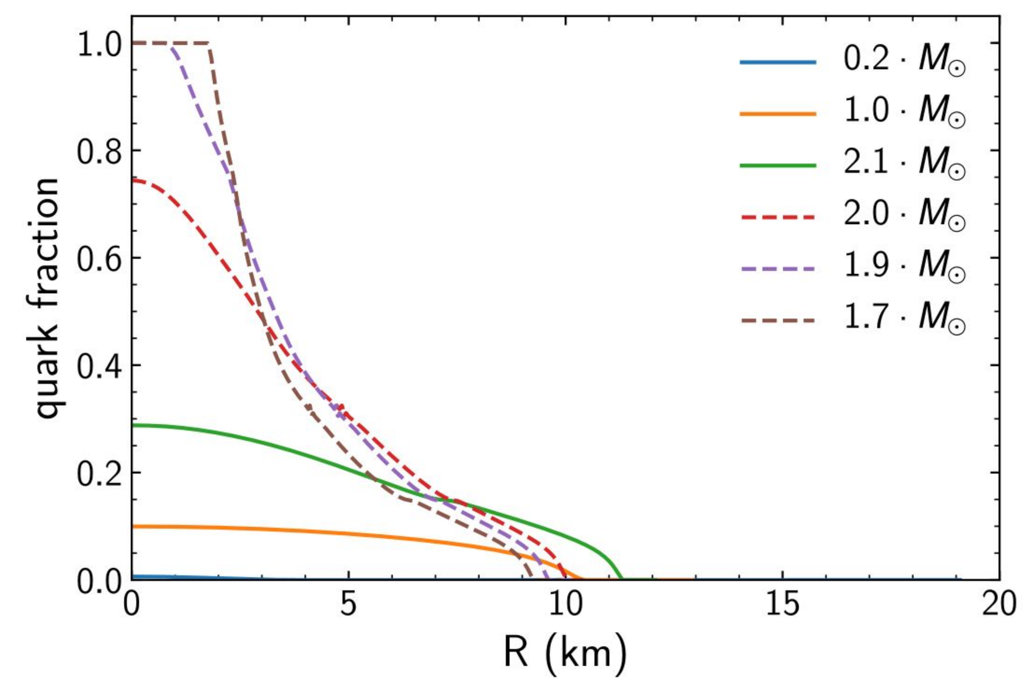
ISENTROPIC TRAJECTORIES FROM SHOCK WAVE SOLUTION



Entropy produced in a heavy ion collision — from Taub adiabat and then isentropic expansion until freezeout.

APPLICATION TO NEUTRON STARS

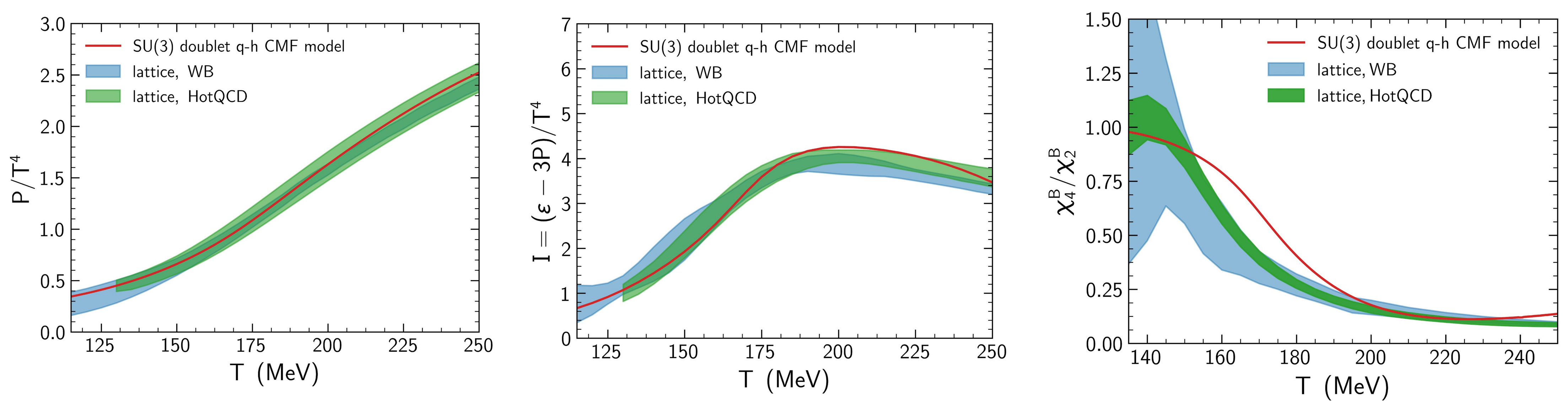




Model gives an equation of state for cold nuclear matter in β-equilibrium — necessary input for modeling neutron stars.

- **Produces a mass-radius relation that is in agreement with known properties of neutron stars.**

Properties at μ_B=0



To apply model at high T the parameters of quark sector (parameters of Polyakov potential and quark couplings to scalar fields) were tuned to reproduce the trace anomaly I from lattice data [3,4].

SUMMARY

- The model predicts a **rich phase diagram** with two critical points at low temperature region;
- **Nuclear liquid-gas phase transition** is a main source of fluctuations in the crossover region;
- Transitions to chirally restored phase, and to quark dominated phases are **at very high values** of chemical potential that are **inaccessible** at experiment;
- SU(3) parity doublet quark-hadron is a consistent model for both **hot QCD matter** in heavy-ions collisions and **cold isospin asymmetric matter** inside of neutron stars.

REFERENCES

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[6] Ongoing work

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