Robert Schulze, Burkhard Kämpfer

QCD Equation of State

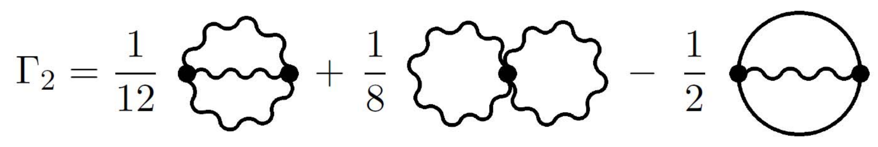
and compact stellar objects from Hard Thermal Loops

Quasiparticle Model

- elementary excitations of the QGP can be interpreted as quasiparticles with medium-modified properties
- derivation of the QCD thermodynamic potential via **Cornwall-Jackiw-Tomboulis formalism**

$$\Gamma[D,S] = I - \frac{1}{2}\left\{\mathrm{Tr}\left[\ln D^{-1}\right] + \mathrm{Tr}\left[D_0^{-1}D - 1\right]\right\} + \left\{\mathrm{Tr}\left[\ln S^{-1}\right] + \mathrm{Tr}\left[S_0^{-1}S - 1\right]\right\} + \Gamma_2[D,S]$$

from a 2-loop QCD functional

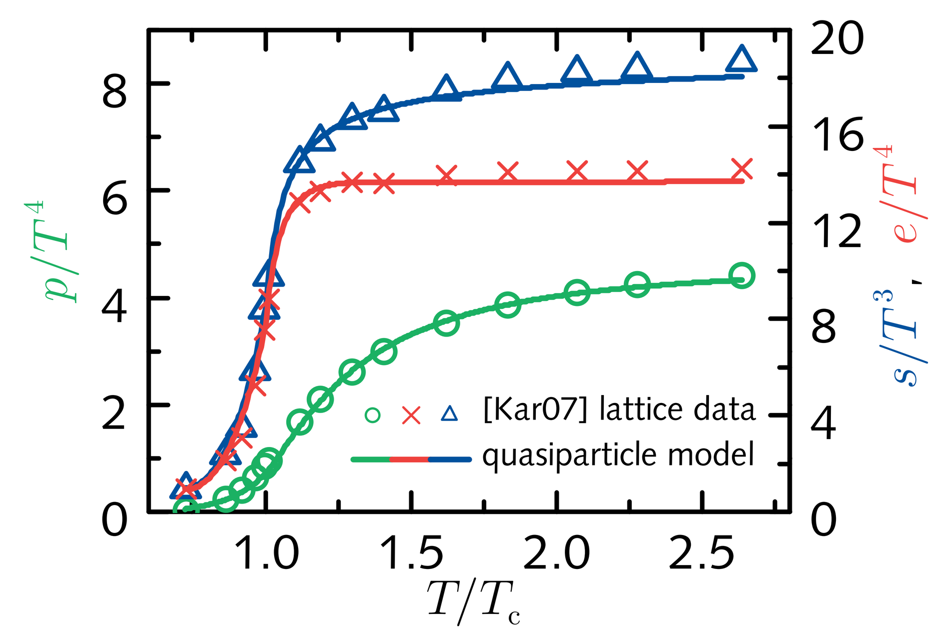


- gauge invariance ensured by using hard-thermal loop (HTL) self-energies in dispersion relations $\omega(k)$
- contributions from quasiquarks and -gluons, plasmons and plasminos, also Landau damping, to entropy density give

$$s := \frac{\partial\Gamma}{\partial T} = s_{g,\mathrm{T}} + s_{g,\mathrm{L}} + s_{q,\mathrm{Pt}} + s_{q,\mathrm{Pl}} + s' \qquad s' \approx 0$$

$$s_{g,\mathrm{T}} \sim \int_{\mathrm{d}^4k} \frac{\partial n_{\mathrm{B}}}{\partial T}\Big\{\underbrace{\pi\varepsilon(\omega)\Theta(-\mathrm{Re}D_i^{-1})}_{\text{quasiparticle contribution}} + \underbrace{\mathrm{Re}D_i\,\mathrm{Im}\Pi_i - \mathrm{atan}\left(\frac{\mathrm{Im}\Pi_i}{\mathrm{Re}D_i^{-1}}\right)}_{\text{Landau damping}}\Big\}$$

- neglecting collective excitations and Landau damping leads to previous simple model (eQP)
- non-perturbative effects of QCD are accommodated by means of an **effective coupling** G^2 replacing running coupling entering HTL self-energies
- adjustment of model parameters in G^2 to **first principle** lattice **QCD** calculations of pressure and entropy density from Karsch, 2007 at $n=0$



Equation of State

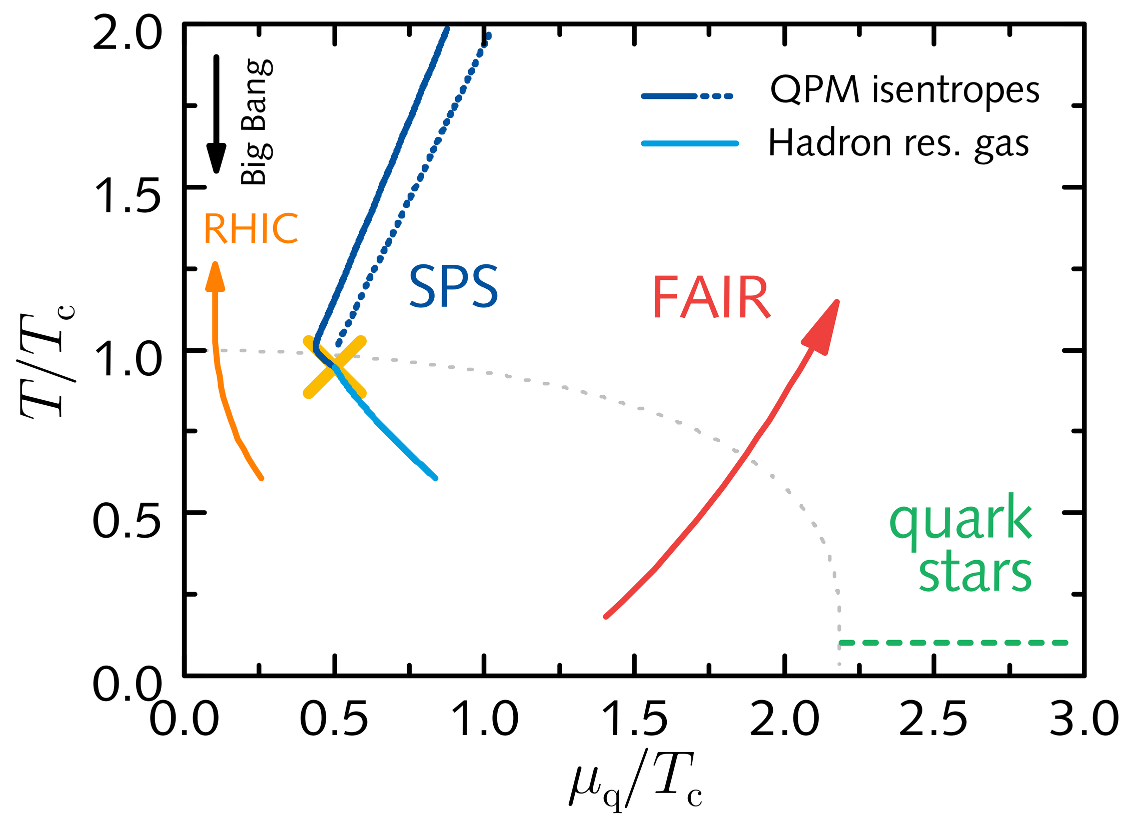
- self-consistent model allows **mapping to nonzero baryon densities** using Maxwell's relation

$$\frac{\partial s}{\partial \mu} = \frac{\partial n}{\partial T}$$

→ 1st order partial differential equation for G^2 (dubbed "**flow equation**")

$$a_T(\mu,T)\frac{\partial G^2}{\partial T} + a_\mu(\mu,T)\frac{\partial G^2}{\partial \mu} = b(\mu,T,G^2)$$

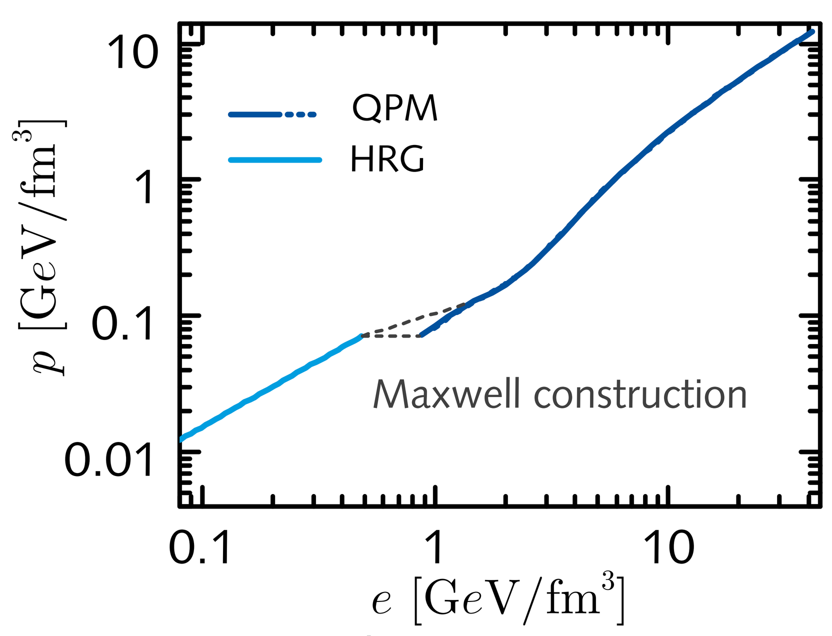
→ method of characteristics – free of ambiguities found for eQP close to deconfinement transition

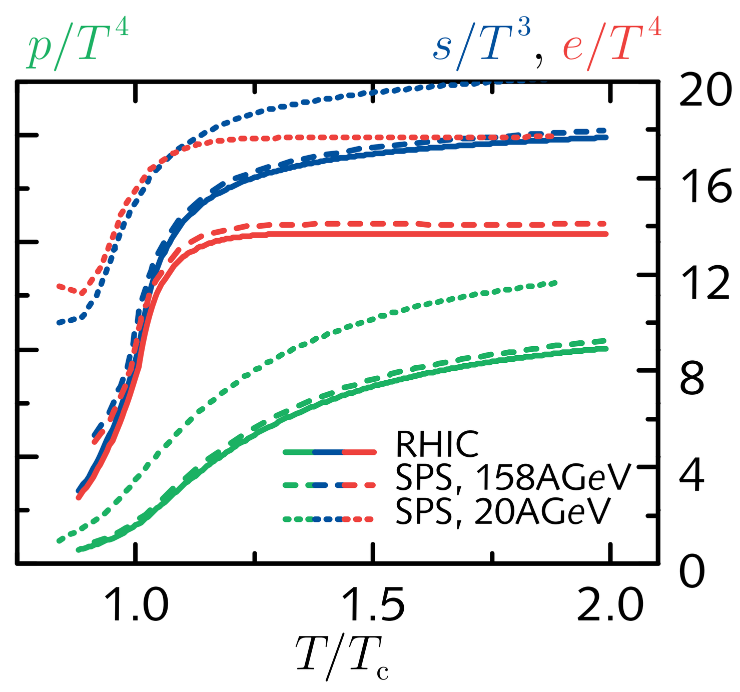


- connect to **hadron resonance gas** (HRG) below the phase transition – Maxwell construction for all state variables

→ both, real phase transition (1st+ order) or simple crossover possible

- Equation of State for heavy-ion collision experiments as well as compact stellar matter available



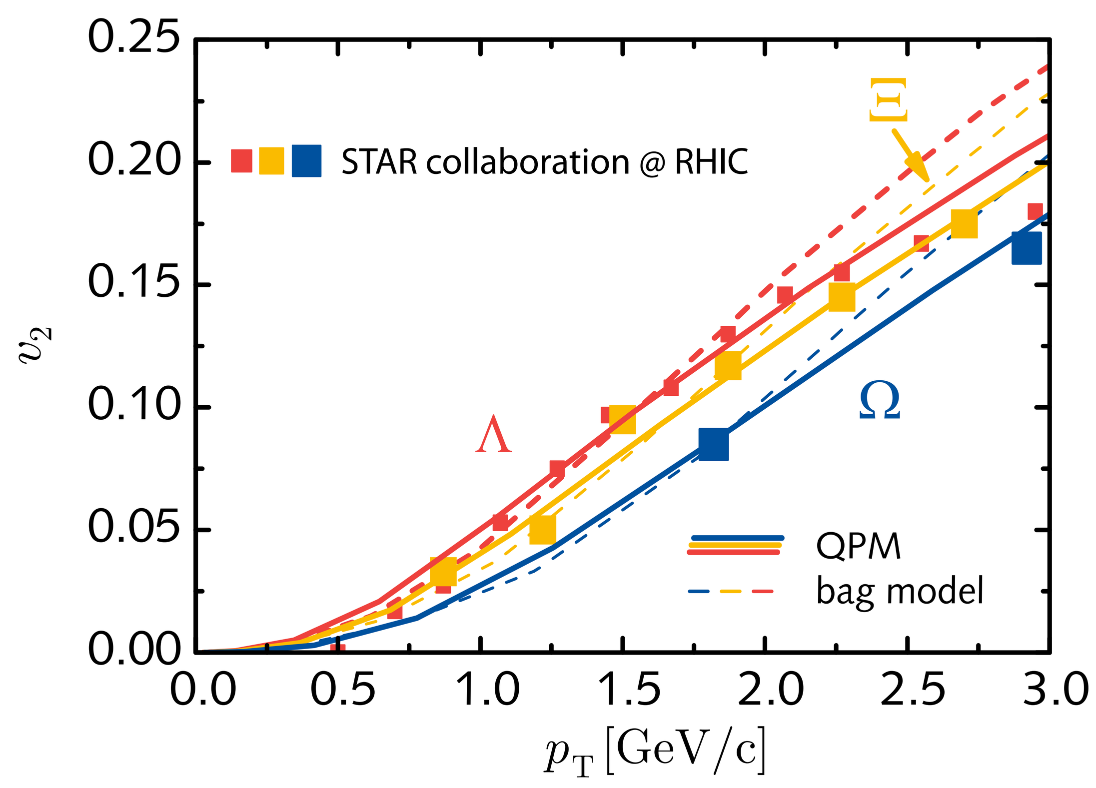


- evolution of state variables with increasing particle densities is shown in right panel

→ pressure p, entropy density s, energy density e, baryon density n_{Ba} and interaction measure $e\text{-}3p$ increase with baryo-chemical potential

→ quantities obey standard thermodynamic relations such as Nernst's law

- EoS applied in hydrodynamic descriptions of HIC - comparison with **experimental results** from STAR collaboration: elliptic flow v_2 (measure of azimuthal distribution of emitted hadrons) as function of transverse momentum p_{T}



Quark stars

- EoS for small temperatures and large baryon densities can be parametrized as a Bag-like system

$$e = \alpha p + 4\tilde{B}$$

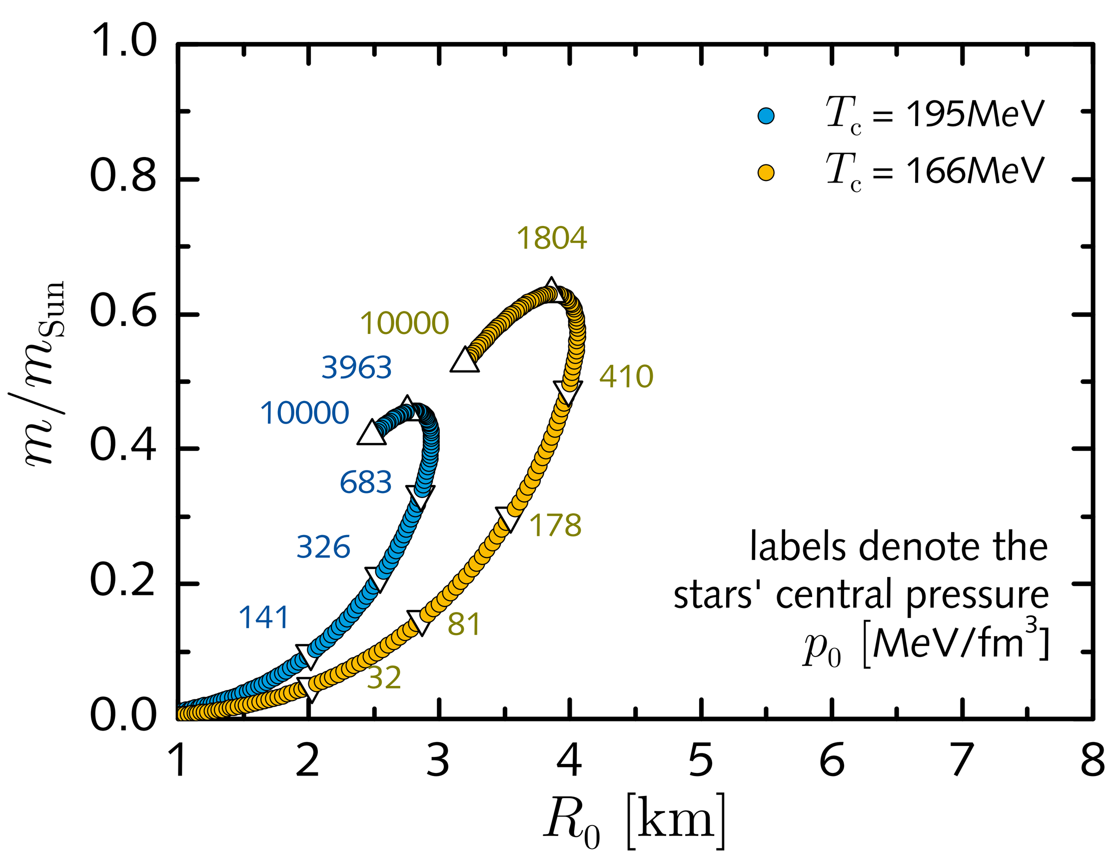
where α is found to be approximately 4 as opposed to 3 from previous quasiparticle models

- β-equilibrium between quarks, gluons and leptons maintained by weak processes

$$d, s \leftrightarrow u, l, \nu_l$$

→ lepton chemical potential follows directly from electric charge neutrality

- **Tolman-Oppenheimer-Volkov** equations give dependence of radius and mass of quarks stars on the central pressure
- strong dependence of star radii on value of critical temperature T_c observed



References:

Schulze, Kämpfer – PPNP, to be published

Schulze, Bluhm, Kämpfer – EPJ ST, 2008

Bluhm, Kämpfer, Schulze, Seipt, Heinz – PRC, 2007

Forschungszentrum Dresden Rossendorf

Member of the Helmholtz Association • Bautzner Landstr. 400 • 01328 Dresden/Germany • http://www.fzd.de

Contact: Robert Schulze • Institute of Radiation Physics • Email: r.schulze@fzd.de • Phone: +49 351 4633 - 4619