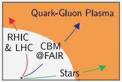


A FAIR equation of state

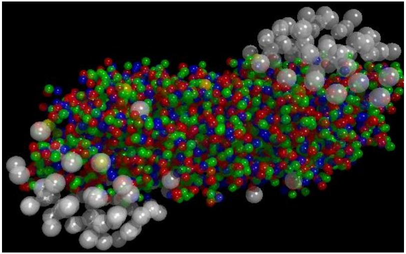
Robert Schulze
FZ Dresden-Rossendorf, FWKH

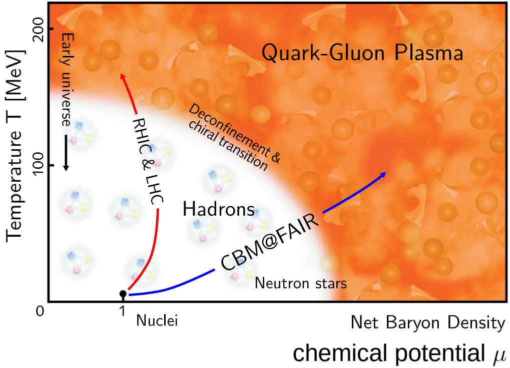
with B. Kämpfer

- quasiparticle model of quarks and gluons
- derivation of an equation of state (EOS)
- application of the EOS @ RHIC, FAIR and for pure quark stars

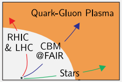
Introduction

- protons and neutrons consist of quarks and gluons
- heavy-ion collision experiments:
  formation of quark-gluon plasma (QGP)





Introduction (2)

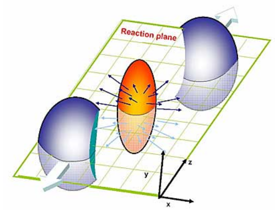


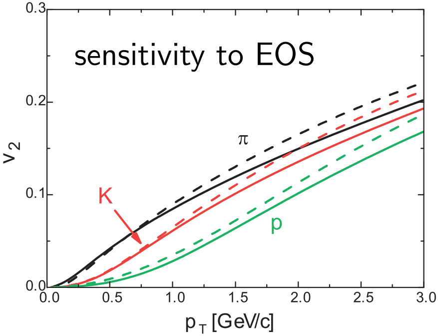
- fireball phase described using hydrodynamics

  $\longrightarrow$ equation of state (EOS) of quark-gluon plasma is critical input

- example: azimuthal distribution v_2 @ RHIC

$$\frac{\partial N}{\partial \phi} = v_0 + v_1 \cos\phi + v_2 \cos 2\phi + \ldots$$

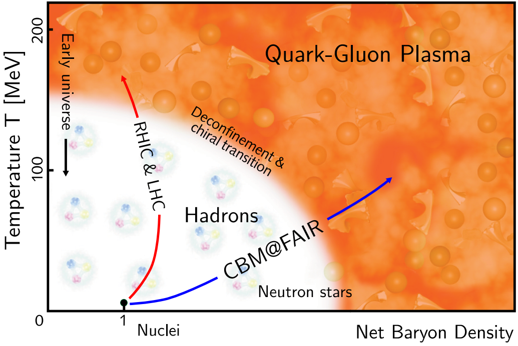




Bluhm, Kämpfer, RS, Seipt, Heinz: PRC'07

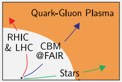
Introduction (3)

- 1^{st} principle evaluation of QCD difficult:
  - perturbative only if coupling weak
  - Monte-Carlo methods "on the lattice" only if baryon density low



$\longrightarrow$ quasiparticles to the rescue

The quasiparticle model



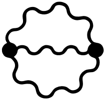
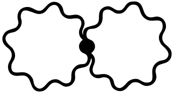
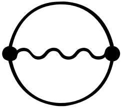
- quasiparticle model = thermodynamic system; thermodynamic potential: pressure $p(T, \mu)$

  $\longrightarrow$ other quantities follow

  chemical potential

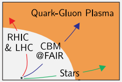
$$s = \frac{\partial p}{\partial T} \qquad n = \frac{\partial p}{\partial \mu}$$

- derived as approximation to actual QCD: CJT formalism with 2-loop Γ_2-functional

$\Gamma_2 = \frac{1}{12}$  $+ \frac{1}{8}$  $- \frac{1}{2}$ 

RS, Bluhm, Kämpfer: EPJ ST'08

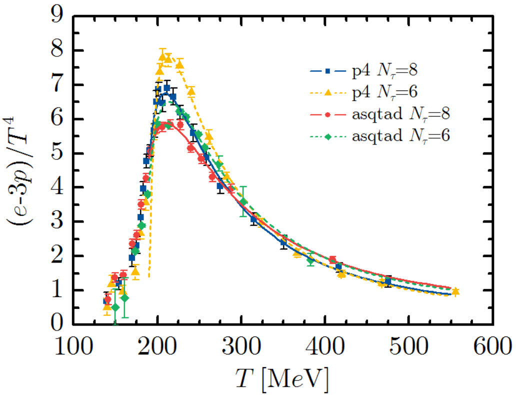
The quasiparticle model



- fundamental parameter:
  running QCD coupling constant G^2

$$g^2(x^2) = \frac{16\pi^2}{\beta_0 \ln(x^2)} \qquad x = \frac{\bar{\mu}}{\Lambda_{\mathrm{QCD}}} \rightarrow \frac{T\text{-}T_s}{\lambda}$$

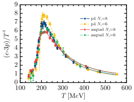
$\longrightarrow$ description of lattice results possible !

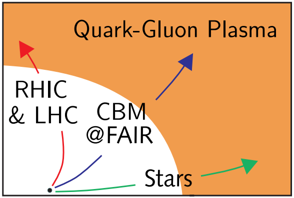


state variables s, n, p, $(e\text{-}3p)$, ...

effective coupling G^2 (+ pressure constant B_0)

@ $\mu = 0$:

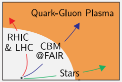




@ $\mu \neq 0$:

??

Into the T-μ-plane



- the BIG trick: $\mu > 0$: thermodynamic model $=$ self-consistent

$$\frac{\partial^2 p}{\partial T \partial \mu} = \frac{\partial^2 p}{\partial \mu \, \partial T}$$

$$\downarrow$$

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

$$\downarrow$$

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

Maxwell's relation

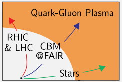
= in a self-consistent system, information in T-direction contains knowledge about μ-direction

flow equation

= Cauchy problem

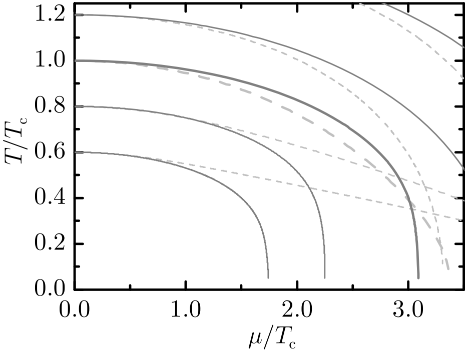
Peshier, Kämpfer, Soff: PRC'00, PRD'02
Bluhm, Kämpfer, RS, Seipt: EPJC'07

Into the T-μ-plane



- solution of the flow equation using method of characteristics
- effective QPM: crossing characteristics
  $\longrightarrow$ area of ambiguous results
- full HTL QPM: crossings resolved
  $\longrightarrow$ large μ, e.g. for FAIR accessible

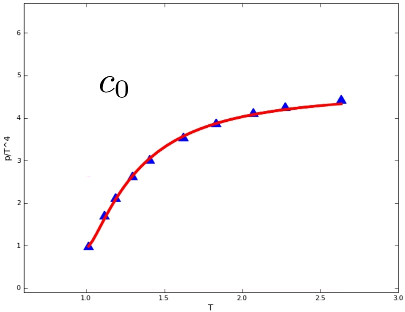
RS, Bluhm, Kämpfer: EPJ ST'08

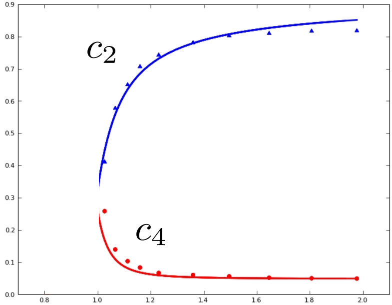


Small chemical potential

- successful test with $p(T, \mu \gtrsim 0)$ lattice data

$$p = T^4 \sum_n c_n(T) \left(\frac{\mu}{T}\right)^n \qquad c_n(T) = \frac{1}{n!} \frac{\partial^n (p/T^4)}{\partial(\mu/T)^n}$$



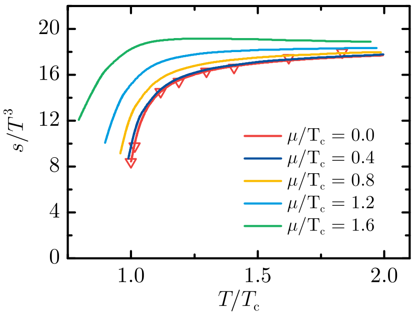


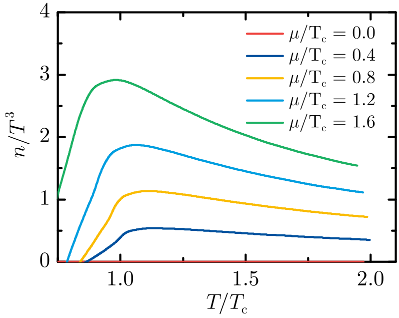
symbols = lattice QCD from Allton et al. (2001)

RS: unpublished

Thermodynamic bulk variables

- entropy density and net quark density



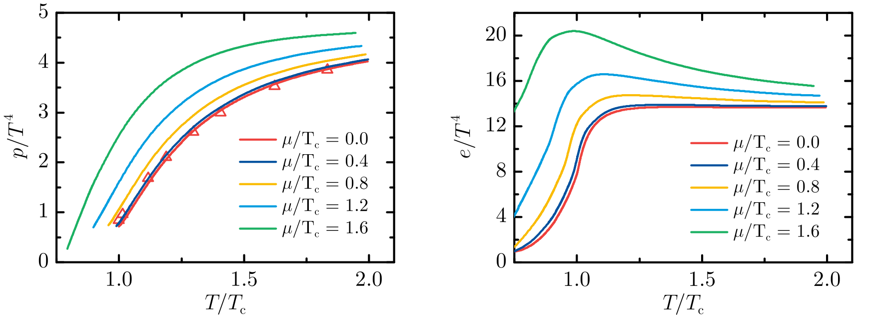


RS, Bluhm, Kämpfer: PPNP'09

- increase with chemical potential

Thermodynamic bulk variables

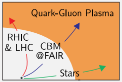
- pressure and energy density



RS, Bluhm, Kämpfer: PPNP'09

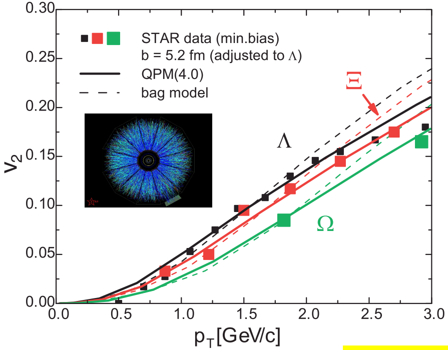
- small area of negative pressure
  $\longrightarrow$ no problems for EOS @ RHIC, LHC, SPS, FAIR
  $\longrightarrow$ natural limit of stability for quark stars

Comparison with the experiment



- calculate elliptic flow using relativistic hydro code using QPM equation of state

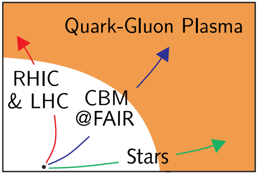
- compare with experimental data (RHIC)



Bluhm, Kämpfer, RS, Seipt, Heinz: PRC'07

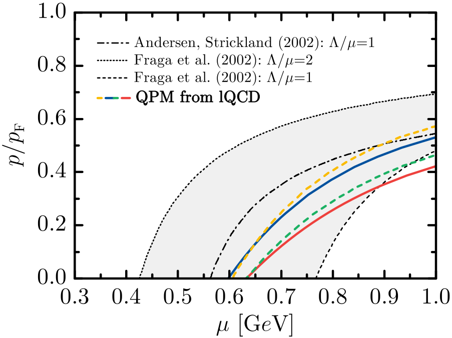
At $T=0$

- going all the way: quarks stars
  → solve TOV equations using QPM equation of state



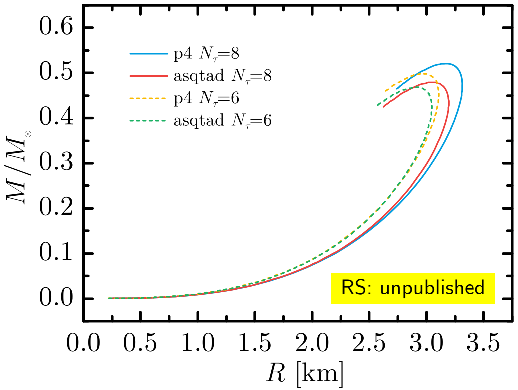
RS: unpublished

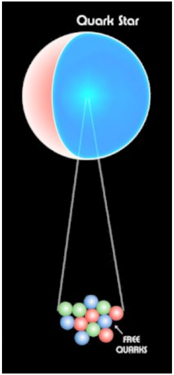
- perturbative predictions for general pressure behavior
  → agreement
  → our estimate = 1st to give an actual order of magnitude



Quark stars

- solutions of the TOV equations





$\longrightarrow$ quark stars quite small and light
$\longrightarrow$ no twins of neutron stars

Summary & Outlook

- EOS adjusted to numerical QCD evaluation
- sound extrapolation to very dense matter
- quark stars with rather smaller radii

- method applicable to EOS of electron-positron plasma for laser-induced hot dense matter

- outlook: EOS for FAIR/CBM:
  combination with hadron EOS