Phases and properties of quark matter

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New results: 1

- The finite-temperature phase transition is a cross over: verified by the Budapest-Wuppertal group (Aoki *et al.*, hep-lat/0611014), confirmed by the Brookhaven-*et al.*(BBRC) collaboration (Cheng *et al.*, hep-lat/0608013), further confirmation awaited from the Hot-QCD collaboration.
- The cross over temperature: temporarily in dispute. Old global analysis (SG, hep-lat/0010011) gave $T_c \simeq 175$ MeV with 20 MeV uncertainty from scale setting. BBCR and Hot-QCD prefer the upper end, BW prefer the lower end and a large spread.
- Deconfinement occurs at the chiral cross over point: linkages between quantum numbers change (Gavai and SG, hep-lat/0510044).
- The equation of state: more later
- Phase diagram for 2+1 flavours: more later.

New results: 2

- Transport coefficients: steady and slow advance (Aarts *et al.*, hep-lat/0703008; Meyer, arXiv:0710.3717).
- Casimir scaling: renormalized Polyakov loop measurements in various representations give strong evidence for Casimir scaling to all orders (Hubner *et al.*, arXiv:0711.2251).
- Chiral fermions at finite chemical potential: some developments (Gattringer *et al.*, arXiv:0704.0092, arXiv:0708.0935; Bloch *et al.*, arXiv:0704.3486, arXiv:0710.0341; Gavai *et al.*, 2008).
- Further studies of isospin chemical potential, imaginary chemical potential. (Splittorff and Svetitsky, arXiv:hep-lat/0703004; Conradi and d'Elia, arXiv:0707.1987; Kogut and Sinclair, arXiv:0709.2367, arXiv:0712.2625; Cea *et al.*, arXiv:0712.3755).
- Phase structure for $SU(N_c)$ colour: $N_c \geq 4$ (Myers and Ogilvie, arXiv:0707.1869; Datta and SG, in progress).
- Wilson quark thermodynamics (Maezawa arXiv:hep-lat/0702005; Chen and Luo, arXiv:hep-lat/0702025; Creutz, arXiv:0706.1207).

New results: 3

- Algorithmic studies at finite chemical potential.
- Charmonium: further verification of J/ψ non-melting and χ_c melting (Döring *et al.*, arXiv:hep-lat/0702009; Aarts *et al.*, arXiv:0705.2198; Umeda arXiv:0710.0204).
- Localization of staggered Dirac eigenvectors: sets in abruptly at T_c, but could be a finite volume artifact. (Gavai *et al.*, 2008).
- Dirac eigenvalues and random matrix theory at finite temperature and chemical potential
- Thermodynamics of $SU(3)$ theory in 2+1 dimensions (Petersson, poster session)
- Topological objects at finite temperature
- $SU(2)$ gauge theory thermodynamics
- Continuum studies of finite volume effects (Gliozzi, arXiv:hep-lat/0701020).

Lattice presentations

- Session X: Schmidt
- Session XI: Karsch, Fodor, de Forcrand, Sharma
- Posters: Gupta and Soltz, P. Hegde, S. Chatterjee, M. Cheng.

Equation of state

- Well determined for quenched QCD as well as for QCD with $N_f = 2 + 1$ (realistic m_π and m_K using staggered quarks by BW, $m_\pi \simeq 220$ GeV and realistic m_ϕ using P4 quarks by BBCR).
- The equation of state in the form $P(E)$ is an important input into hydrodynamics.
- For conformal matter, $P = E/3$ so that $c_s^2 = 1/3$.
- Many toy models of QCD which can be solved using AdS/CFT techniques demand conformal symmetry for the stress tensor, *i.e.*, $P = E/3$. These toy models also use $N_c \to \infty$.

$SU(3)$ Equation of state

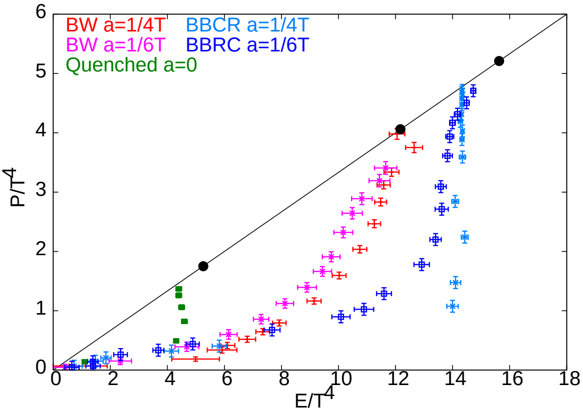

Figure: Quenched data from Gavai *et al.*, hep-lat/0506015; $N_f = 2+1$ data from Aoki *et al.*, hep-lat/0510084; Cheng *et al.*, arXiv:0710.0354 Peak $(E-3P)/T^4$ at $N_t = 8$ (HotQCD) drops by 20% from $N_t = 6$; no change for $T > 1.5\,T_c$.

$SU(4)$ Equation of state

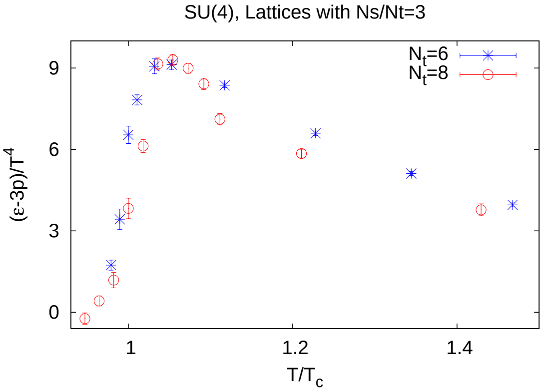

Figure: Strong deviation from conformal symmetry is observed. Datta and SG, in progress. Maximum of $E - 3P$ is at least as large as the latent heat, and hence expected to scale as N_c^2. Thus, conformal symmetry violations will not disappear in the large-N_c limit.

Scaled equation of state

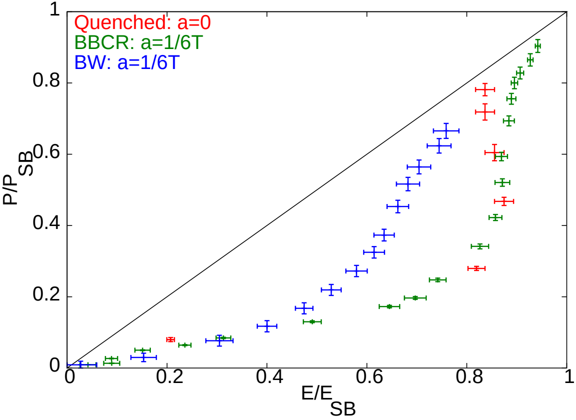

Figure: Quenched data scaled by the $N_f = 0$ continuum SB values, $N_f = 2 + 1$ data scaled by the $N_f = 3$ continuum SB values. Pure gauge theory SB value scales as N_c^2, hence large-N_c limit is expected to (approximately) scale on this figure.

Energy density at T_c

- Quenched QCD $T_c = 285 \pm 10$ MeV SG, hep-lat/0010011.

$$E(T_c) = \frac{16\pi^2}{90} T_c^4 \times 0.75 = (3.4 \pm 0.5)\mathrm{GeV}/\mathrm{fm}^3$$

- $N_f = 2 + 1$ QCD $T_c = 192 \pm 8$ MeV Cheng *et al.*, hep-lat/0608013.

$$E(T_c) = \frac{(16 + 63/2)\pi^2}{90} T_c^4 \times 0.65 = (1.8 \pm 0.3)\mathrm{GeV}/\mathrm{fm}^3$$

Substantially smaller value from Aoki *et al.*, hep-lat/0510084.

Phase diagrams

- Phase diagrams are labelled by the thermodynamic intensive coordinates: T, N_f quark masses and N_f chemical potentials. Experiments can tune (at best) $1 + N_f$ of these.
- Heavy-ion collisions have one control parameter $\sqrt{S}$; cannot examine 4D phase diagram. Vary ions, and smear the line a bit. Still scope for much thought.
- Each point in phase diagram (almost always) is a single pure phase. Exceptions are where two or more phases coexist (first order transitions).
- Continuity argument for lines/surfaces of first order transition called the Gibbs' phase rule, *i.e.*, the structure of solutions of $g_A(T, \mu_i, m_i) = g_B(T, \mu_i, m_i)$. Strongly constrains the topology of phase diagrams.
- Gibbs' phase rule implies: in D dimensional phase diagram, D-2 dimensional critical surfaces, D-3 dimensional tricritical surfaces, D-4 dimensional tetracritical surfaces *etc.*.

The realistic phase diagram of QCD?

Figure: Is this the phase diagram of QCD for realistic quark masses? de Forcrand and Philipsen (2006).

The phase diagram of QCD

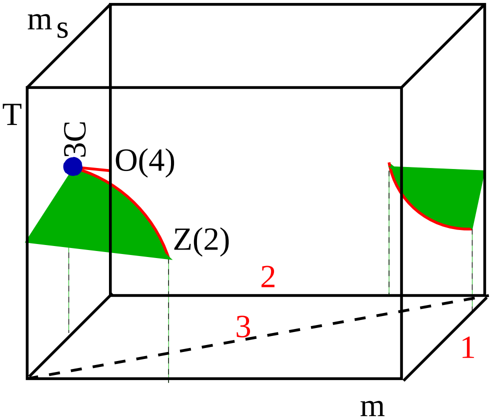

Figure: Put together using computations from Columbia (1990), Bielefeld (2001), and arguments from Pisarski and Wilczek (1984). Some evidence from the lattice that $U_A(1)$ remains broken Edwards *et al.*(2000), Gavai *et al.*, (2002).

The flag diagram of QCD

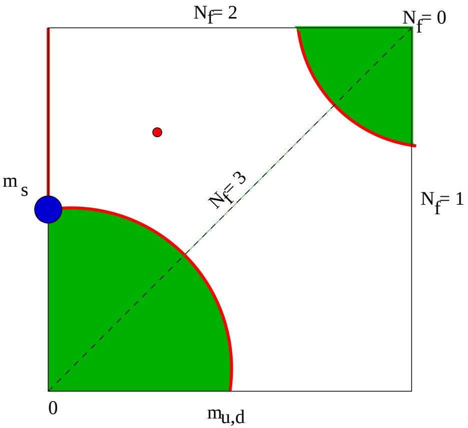

Figure: Project down to the $T = 0$ plane. No longer a phase diagram: each point labels the nature of the phase transition "above" it (not the phase at that point). Call it the flag diagram.

Flag diagram at finite chemical potential

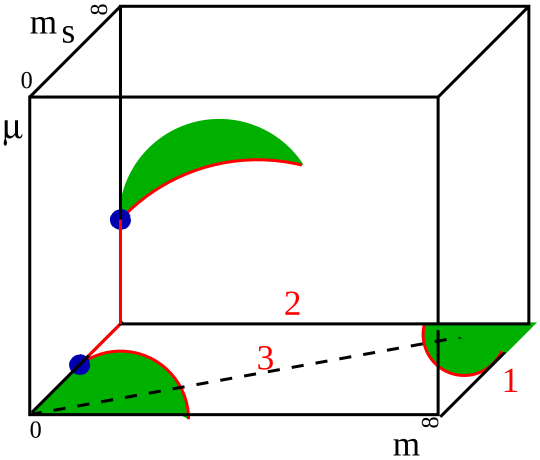

Figure: The plane $\mu = 0$ of this flag diagram is reasonably well explored. The plane of $m_s = \infty$ is reasonably well established.

A Tricritical line

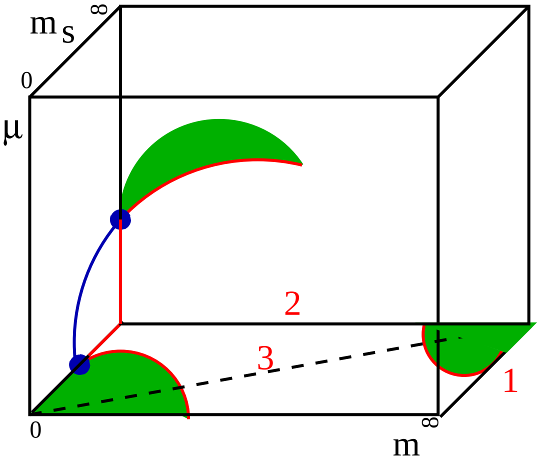

Figure: The two tricritical points are joined by a tri-critical line. This has to lie on the $m = 0$ plane, since there is no $O(4)$ transition unless $m = 0$.

Recent observations

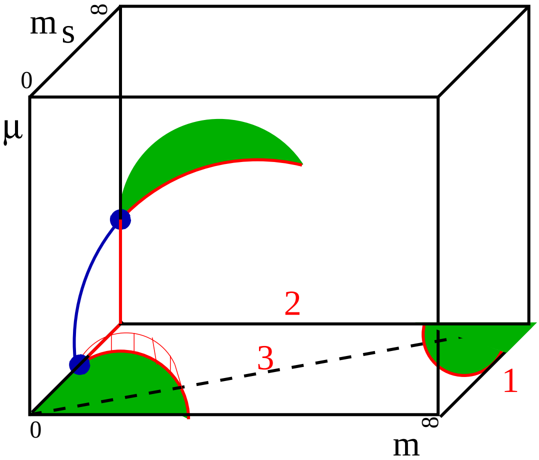

Figure: A part of the critical surface near the $N_f = 2 + 1$ region bends "backwards". Observed by de Forcrand and Philipsen, 2006.

Putting it together

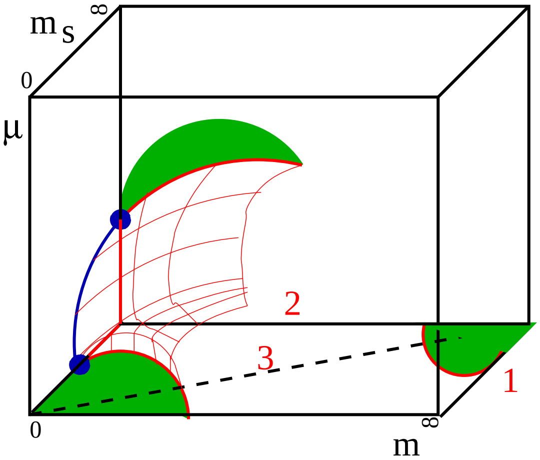

Figure: A second order surface does not have "surface tension", so it can twist and turn. To look at the possible phase diagrams, examine the tricritical line.

Case 1: the simplest

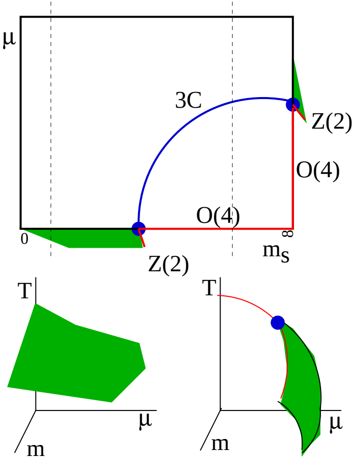

Figure: The simplest possibility is that the tricritical strange quark mass separates the $N_f = 2$ type from the $N_f = 3$ type of phase diagram.

Case 2: a tetracritical point

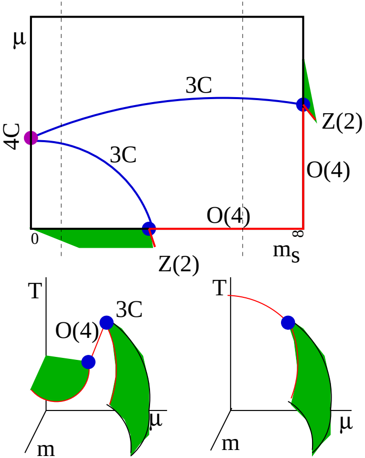

Figure: Is there a tetracritical point? Usually requires high symmetry, but $m_s = m = 0$ is ruled out. Perhaps generic m_s?

Case 3: open sky

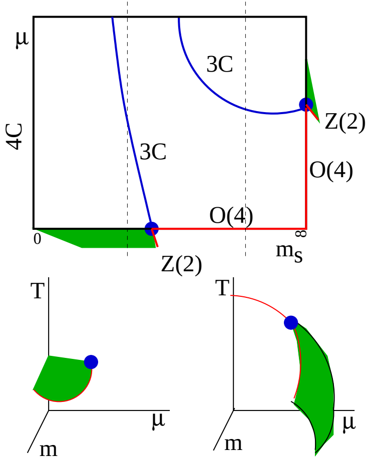

Figure: Pull out the tetracritical point to infinity. This is quite possible. Need to check this in lattice simulations.

Summary

1. Significant progress in lattice computations in the last year. New state of the art is $m_\pi \simeq 220$ MeV, earlier reached only in the computations of BW and M.
2. The equation of state shows that conformal symmetry is strongly broken in the range of temperatures below $3T_c$. There is some evidence that this does not change with increasing N_c. Hydrodynamics needs to take into account bulk viscosity for $T \leq 3T_c$.
3. The phase diagram for $N_f = 2 + 1$ first suggested by de Forcrand and Philipsen may be too pessimistic: their computations are compatible with qualitatively familiar phase diagrams SG, arXiv:0712.0434. Computations are called for.

An announcement

International Centre for Theoretical Sciences (TIFR)

Initial Conditions in Heavy-Ion Collisions
QCD at high parton densities

Program dates: September 1–22, 2008
Advanced School: September 8–12, 2008
International Center, Dona Paula, Goa

Rajiv Gavai, Francois Gelis, Sourendu Gupta, Raju Venugopalan
http://theory.tifr.res.in/˜qcdinit

$SU(4)$: two-loop scaling

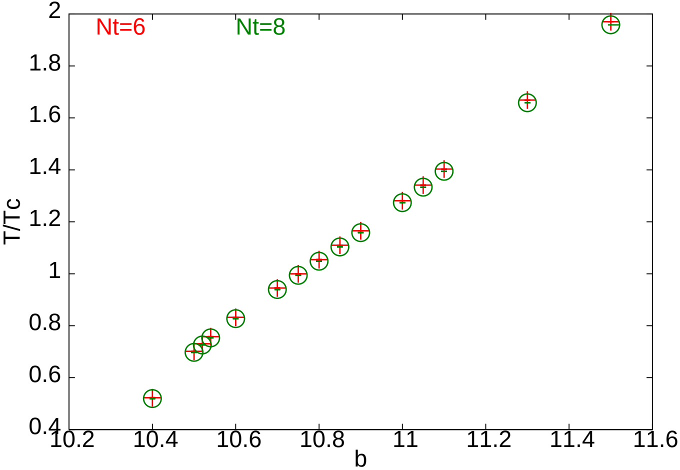

Figure: The scale determination using the two-loop β-function works very well for $N_t \geq 6$. Datta and SG, in progress.

$N_f = 2$ flag diagrams

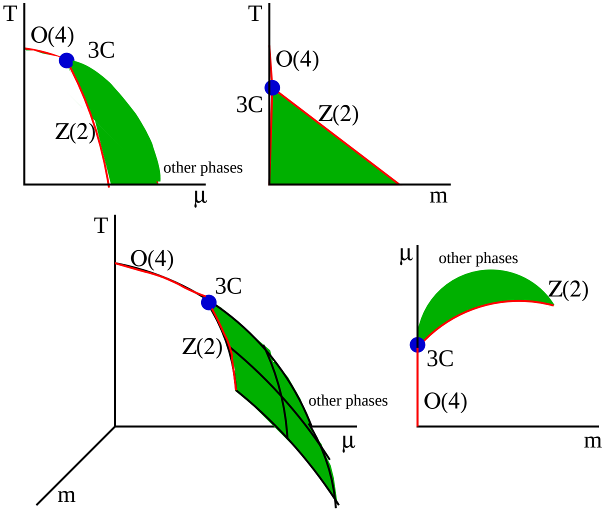

Figure: