Lattice QGP

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15 December, 2006
DAE Symposium
IIT Kharagpur

Plan

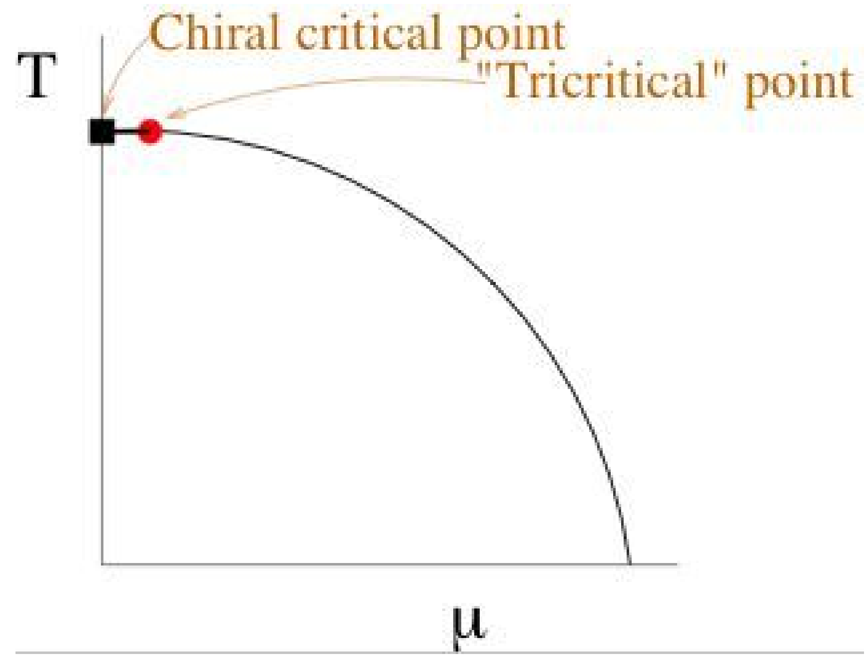
- The crossover temperature: BiBC (hep-lat/0608013), Wuppertal (hep-lat/0609068)
- The QCD phase diagram: de Forcrand and Philipsen (hep-lat/0607017), Mumbai (hep-lat/0412035)
- What the plasma is made of: Mumbai (hep-lat/0510044)
- The equation of state: MILC (hep-lat/0611031), BIKR (hep-ph/0611393)
- The melting of J/Ψ
- Transport coefficients: η and σ
- Screening masses and fluctuation measures

$N_f = 2$

Phase diagram

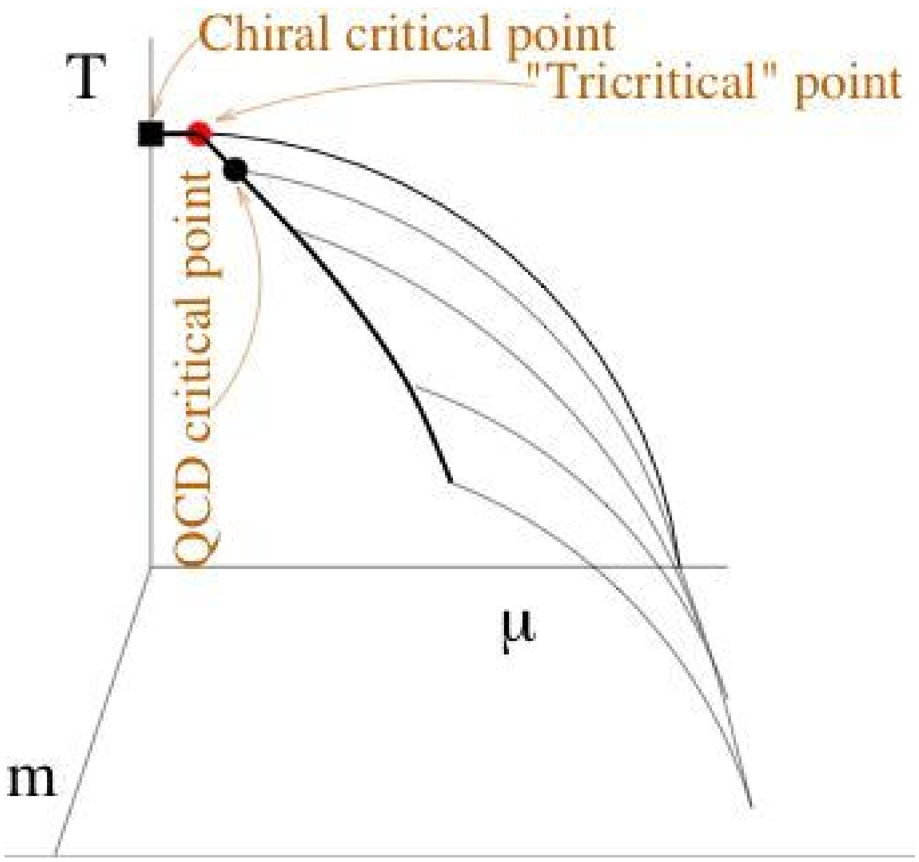
Friendly neighbourhood phase diagram

- QCD phase diagram for two chiral flavours: mu=md=0
- 2nd order transition at m=0 and TC develops into a critical line; turns into 1st order line at the tricritcal point
- Each point of a phase diagram is an unique phase.



Friendly neighbourhood phase diagram

- QCD phase diagram for two flavours has another direction: the light quark mass m
- For any m≠0, there is no phase transition at m=0: only cross over (no divergences or discontinuities)
- Tricritical point develops into a critical point.



$N_f=3$

Phase diagram

Crossover in continuum

- Wuppertal (hep-lat/0609068) computation with fat link staggered quarks: N_t=4,6,8,10
- Scale setting using f_K and Sommer scale r_0 using realistic strange quark masses (ie, m_K/f_K and pion mass m_π/m_K), pion 2 times heavier
- Spatial sizes range from to 3 to 6.7/m_π, which are reasonable. Statistics on the smaller side.
- Different indicators of phase transition do not agree. Typical of crossover. T_c=151±3±3 MeV using χ_m and shifted by 28±5±1 MeV using χ_L.

A different estimate

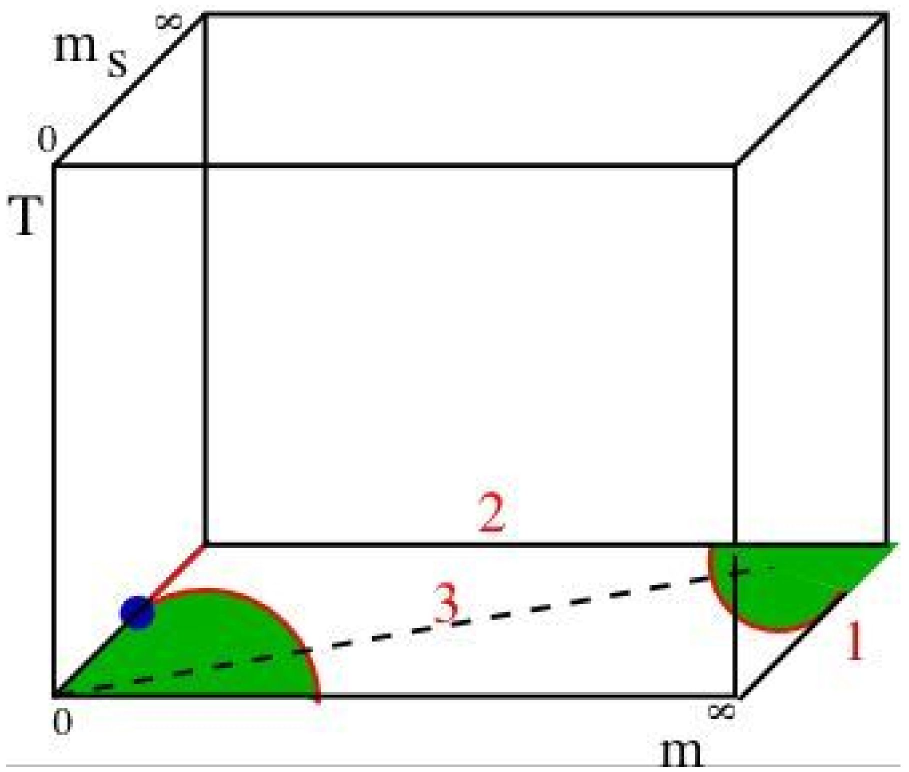
- RBBiC (hep-lat/0608013) compute with $N_t=4$ and 6, $m_{ss}/m_\pi=1.3$ instead of 3.6 (pion 3 times heavier than physical) using p4 action.
- Spatial size of lattice between $3/m_\pi$ and $6/m_\pi$ and 2/3 as large for $N_t=6$.
- MD trajectories are short: autocorrelations could be more than twice as long as Wuppertal (if the action were the same). Decreased effective statistics.
- Scale set by r_0, leads to $T_c=192\pm7\pm4$ MeV.

Previous results

Old estimate by Bi (hep-lat/0012023): Tc=173± 8 MeV using $\sqrt{\sigma}$ to set the scale.

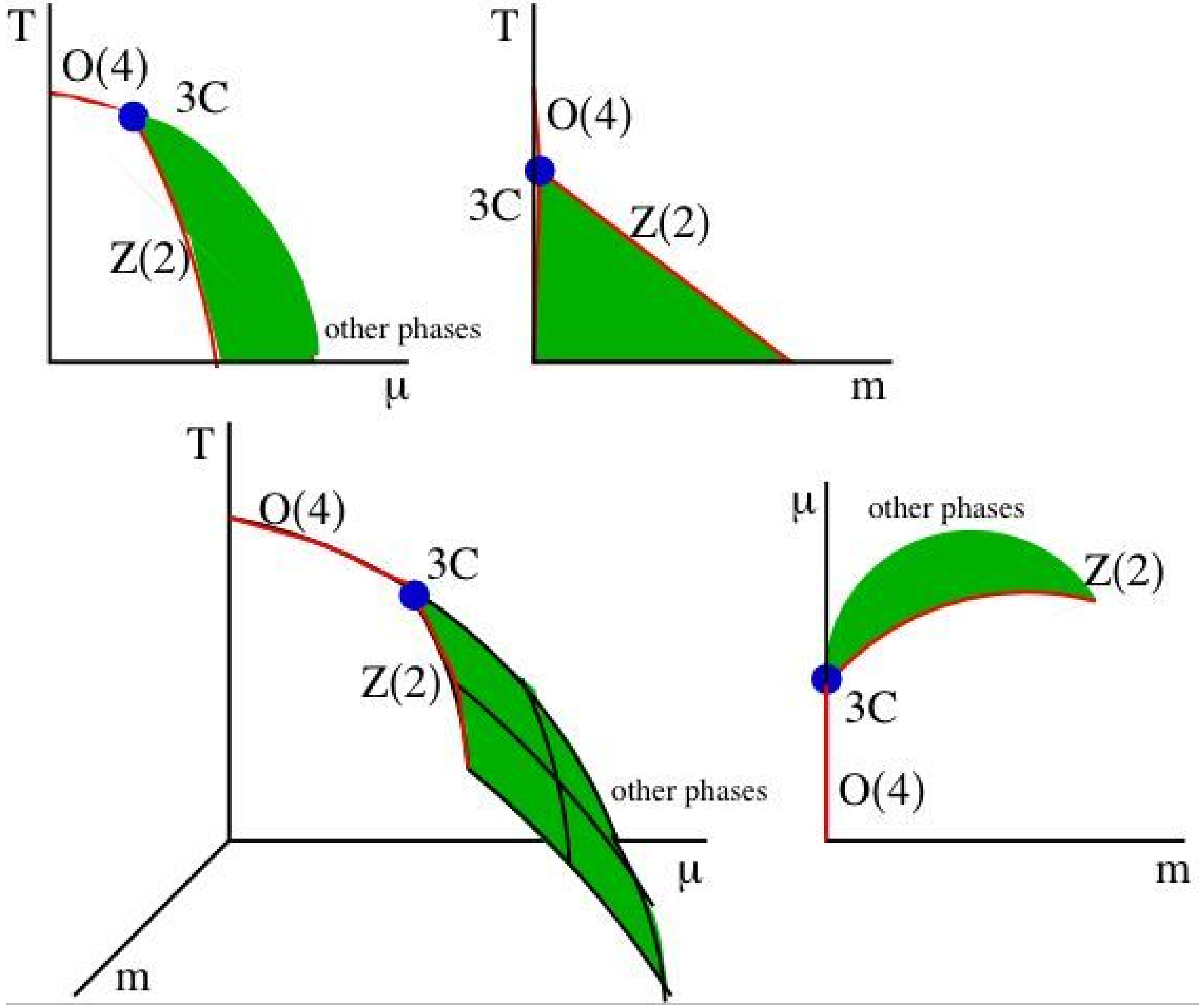
- Global analysis of N_f=2 data from many collaborations (SG, hep-lat/0010011) gave Tc=$167\pm9^{+15}_{-14}$ MeV. Main uncertainty due to scale setting. Used Λ_{QCD} to set the scale.
- RBBiC quotes a 10% upward revision of $\sqrt{\sigma}$ when r_0 is used to set the scale.
- Wuppertal result is within 10% (below) old estimate. Claimed to be due to the continuum limit.
- At the moment, 40% uncertainty in ε.

The phase diagram

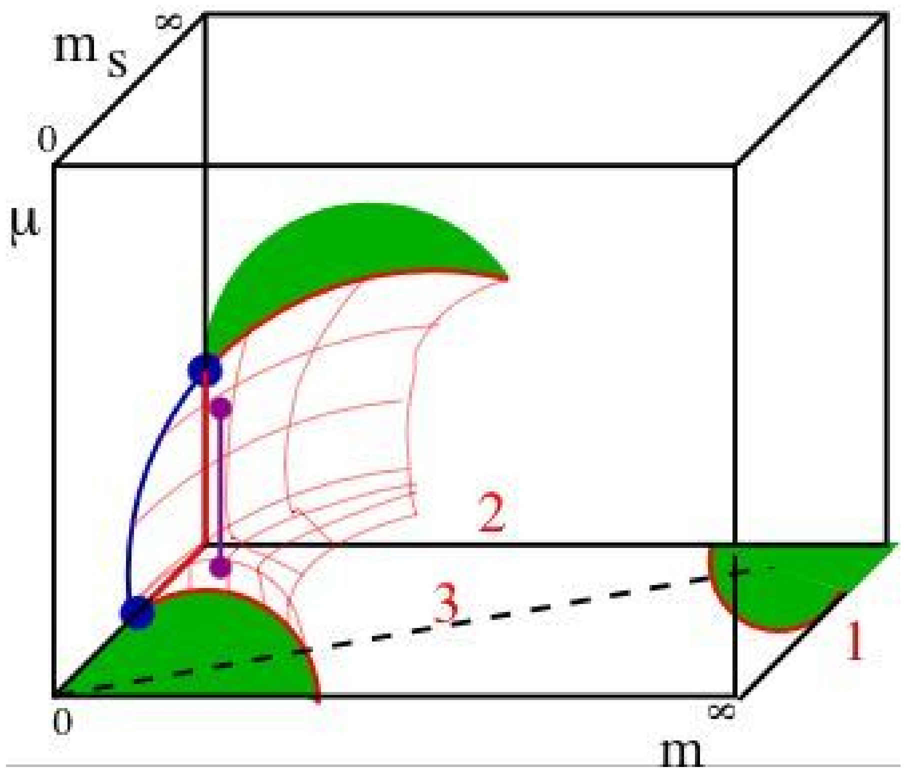


4 dimensional phase space: m, m_s, T, μ.
Project to one less dimension: cut out T

Funny things happen

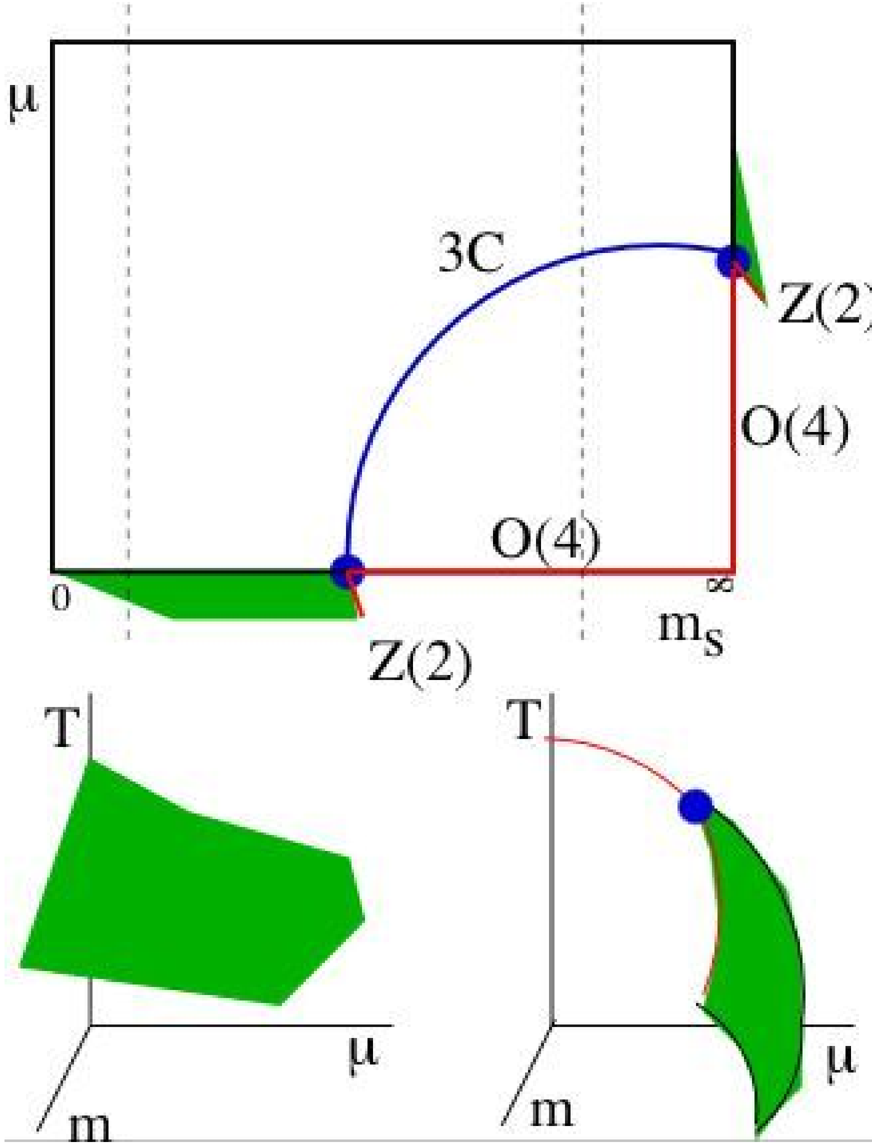


Another dimension



Two O(4) critical lines, two Z(2) critical lines, and two tricritical points organize the phase diagram.

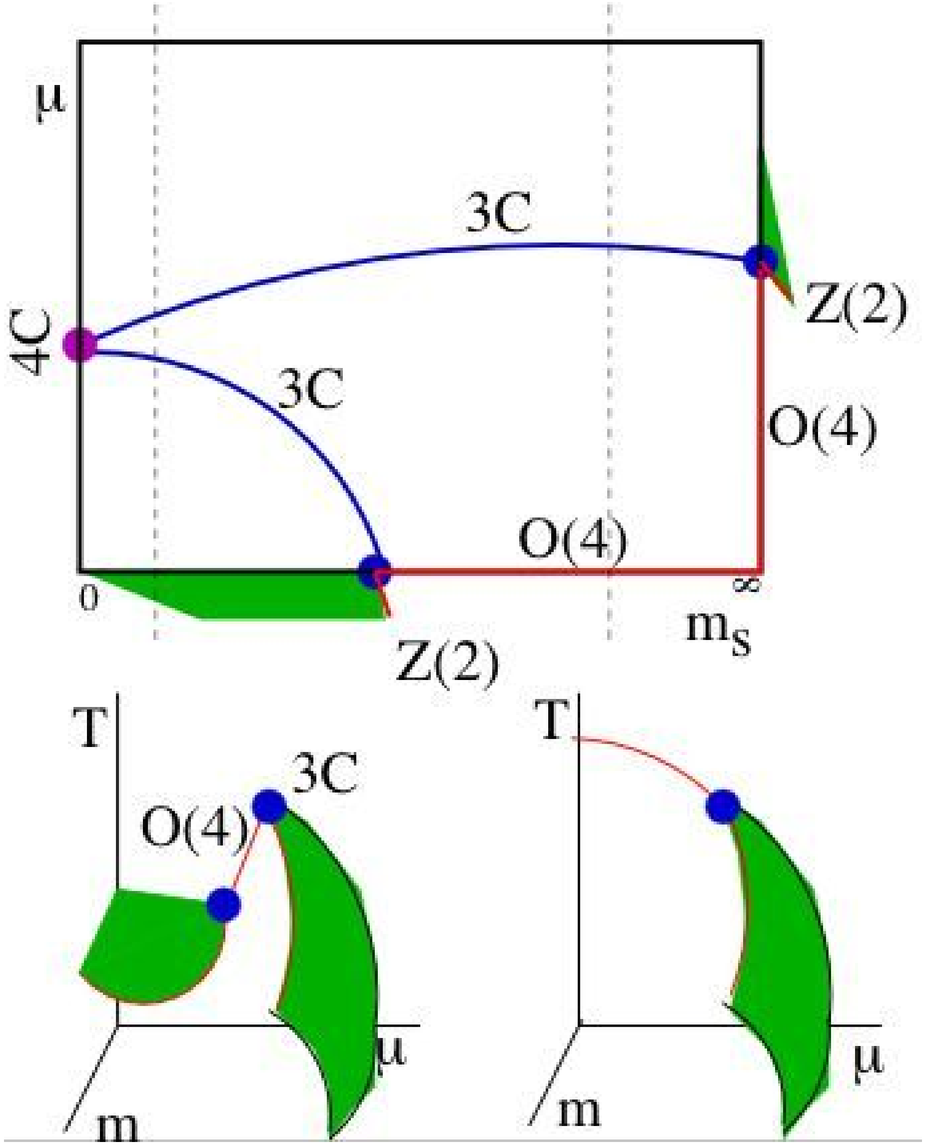
The tricritical line



Standard scenario. 3C line meets μ=0 plane at a point which separates "large m_s" from "small m_s". Above this, the N_f=2 phase diagram is accurate. Dividing line must be $m_s \approx \Lambda_{QCD}$.

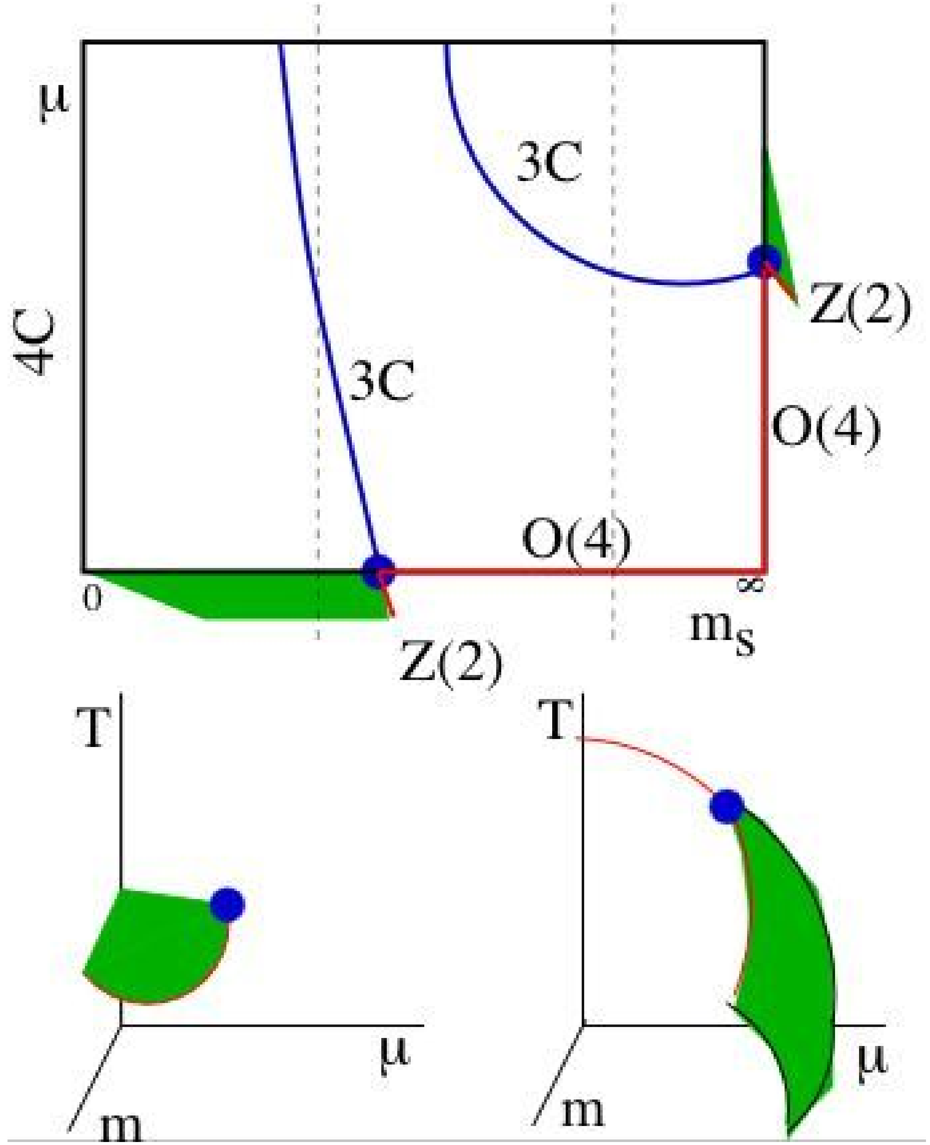
Accurate location of 3C point: future.

A tetracritical point



Two 3C lines meet at a 4C point. But this is a point of higher symmetry. In this phase diagram it can only appear on the m_s=0 line. **4C point in N_f=3 is a new universality class.** Can be ruled out.

Two tricritical lines



4C point can be avoided by taking the end points of the two 3C lines to infinity. Then phase diagram is **qualitatively similar to N_f=2, but quantitatively very different.** Not ruled out. Effective models?

On the method

- deF&P determine the critical line in the $\mu=0$ plane using staggered quarks (2+1 flavours)
- Lattices are very small: $Lm_{\pi}\approx 2$, large finite volume corrections can be expected
- Lattices are coarse, lattice spacing artifacts?
- Repeated the simulations with $\mu/T=2.4i$ and found that the critical line remains fixed.
- Negative slope inferred using non-perturbatively defined RG running. Careful!
- Made a linear fit to data!

Where is the QCD critical point?

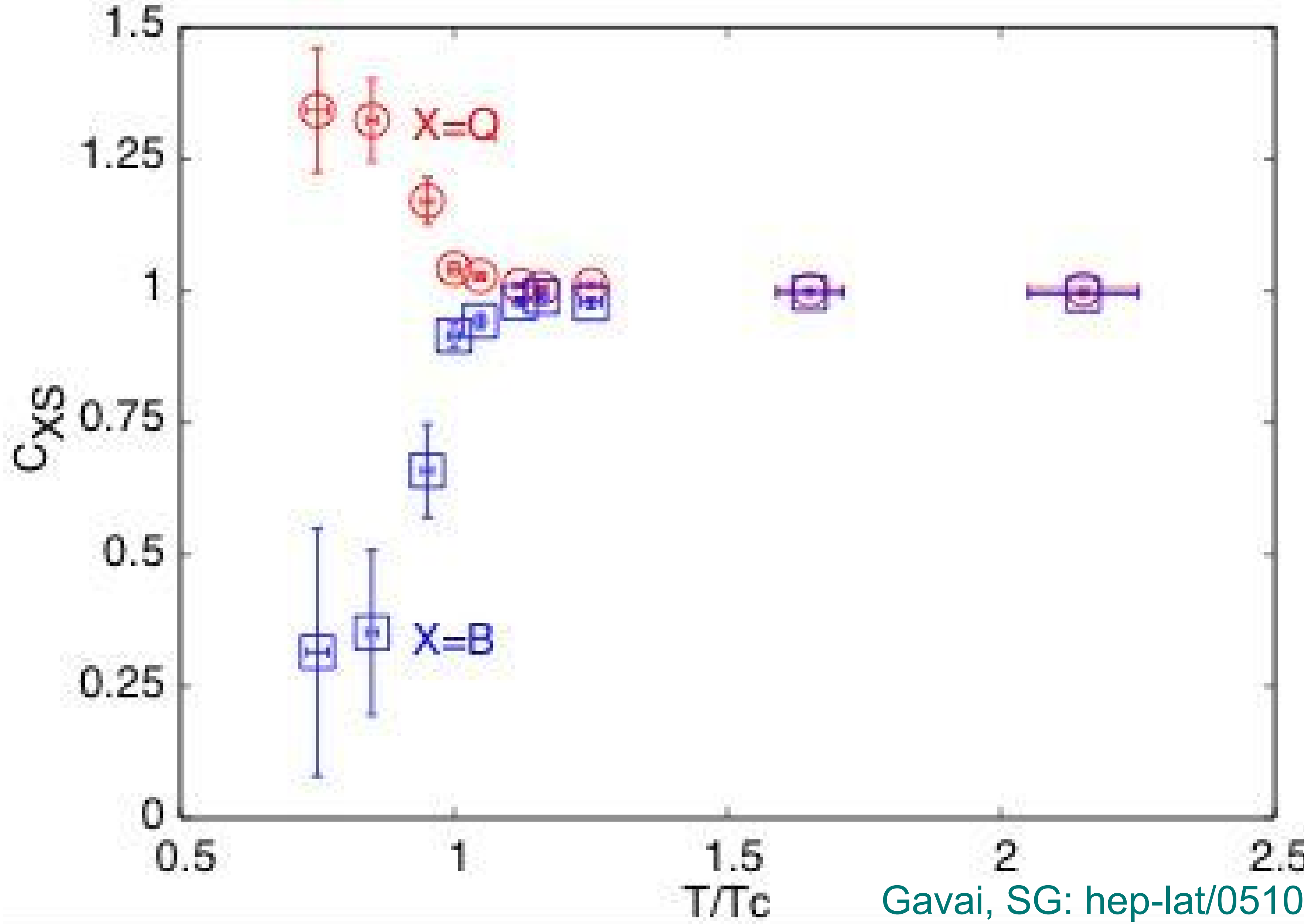
- In the phase diagram shown, there is always a QCD critical point (missed by deF&P). Forced by the fact that $SU(3)_{flav}$ is always broken when $m_s > m$. (3C lines organize the phase diagram)
- If m_s is large enough ($>\Lambda_{QCD}$), then $N_f=2$ is a good quantitative guide to the real world. Is this true in our universe?
- Quantitative estimates for critical end point in $N_f=2+1$ needed in future.
- For now, estimates for $N_f=2$ from Mumbai are that $\mu_e/T_e \sim 1$ **and** $T_e/T_c \sim 0.95$

What is the plasma made of?

Flavour carriers in the plasma

- Look for linkage of two flavour quantum numbers to find light degrees of freedom.
- If K meson then S=1 comes with 3B=0, and 3Q=(3+0)/2=3/2. If s quark then S=1 comes with 3B=-1 and 3Q=1.
- Use fluctuation dissipation theorem to connect these linkages with quark number susceptibilities.
- Examine C_{BS}=-3L(B,S), C_{QS}=3L(Q,S) and C_{ud}=L(u,d) to look for free quarks.

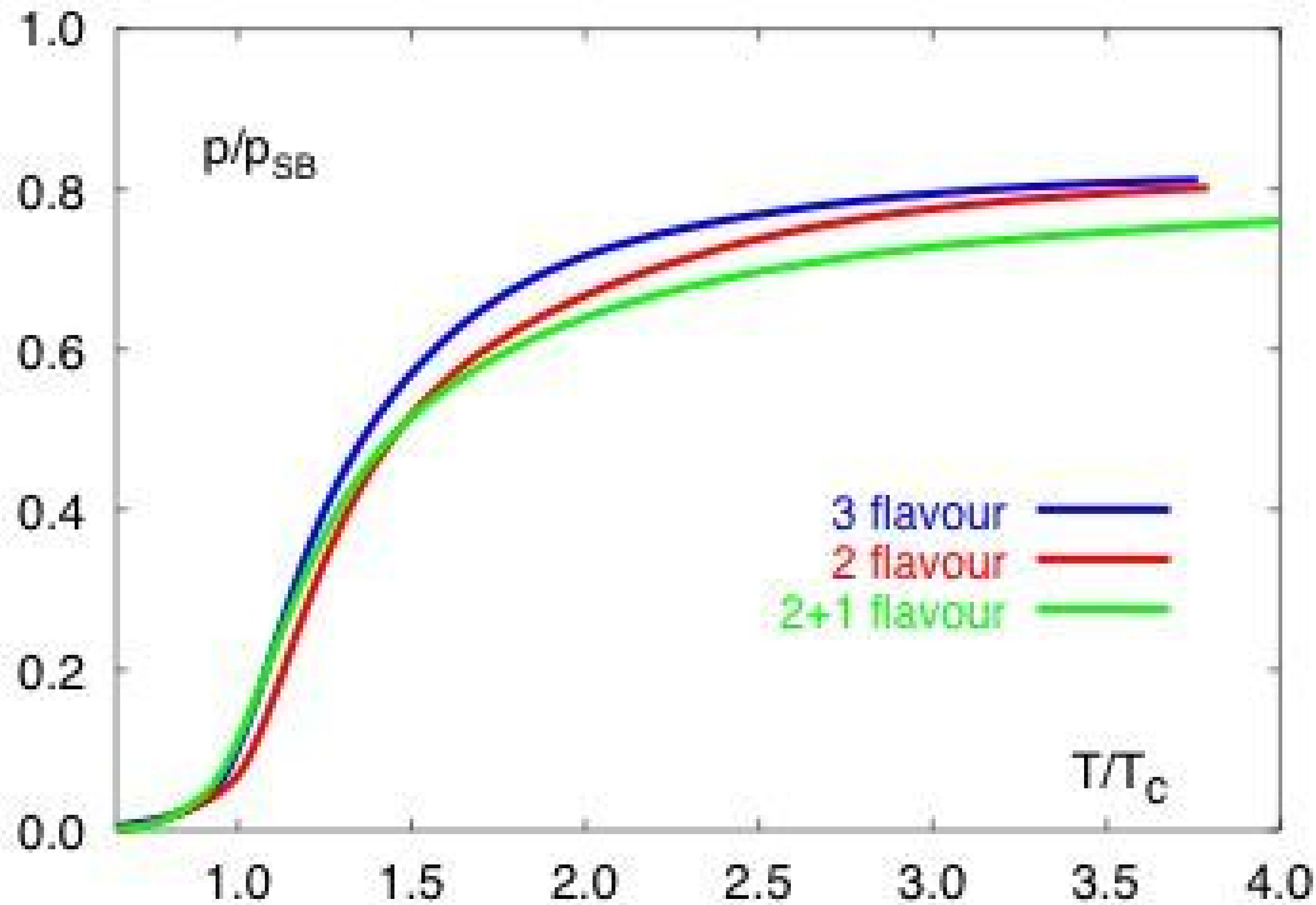
Freedom and equality



Gavai, SG: hep-lat/0510044

The equation of state

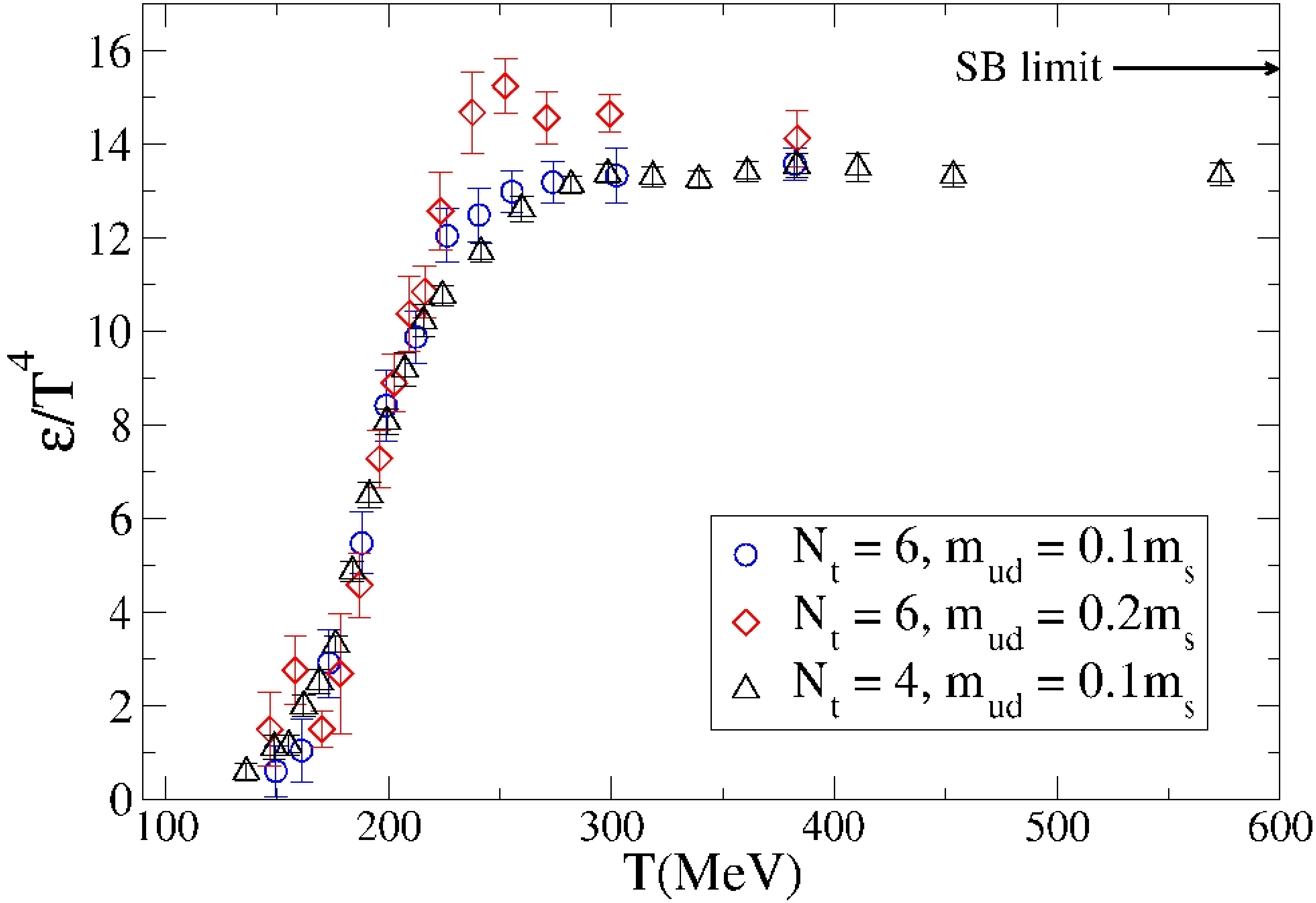
Equation of state: circa 2001



Equation of state: the history

- Lattice computations with quenched QCD showed large departure from ideal gas
- Interaction effects computed in weak coupling have trouble reproducing this data. Dimensional reduction, resummed perturbation theory do better.
- Strong coupling computation using AdS/CFT in toy model called N=4 supersymmetric QCD with $N_c=\infty$. (Note: quarks are adjoint in colour).
- New developments: fermions, weak coupling

New lattice results on EOS

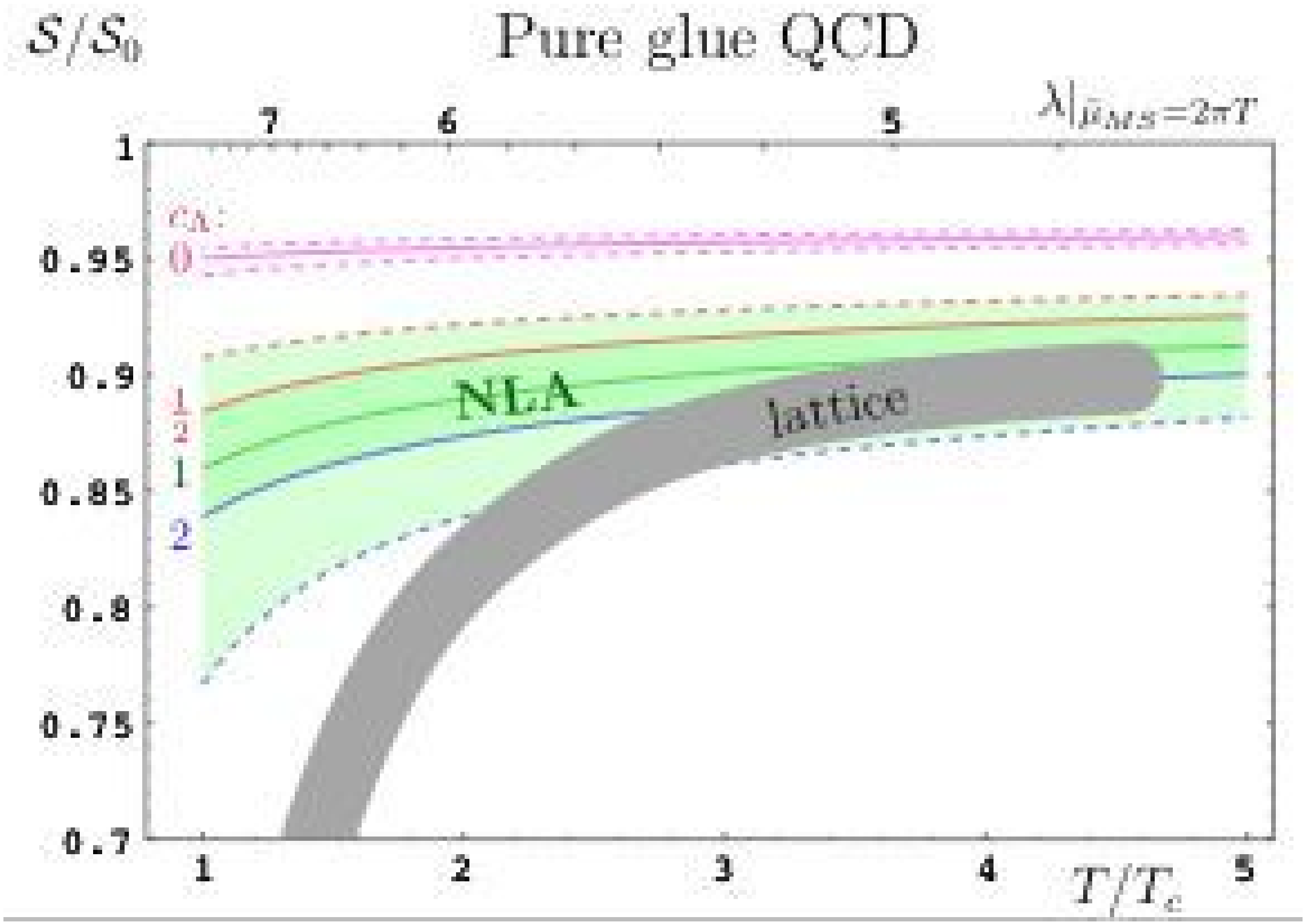


N_f=2+1 with improved staggered quarks. (MILC hep-lat/0611031)

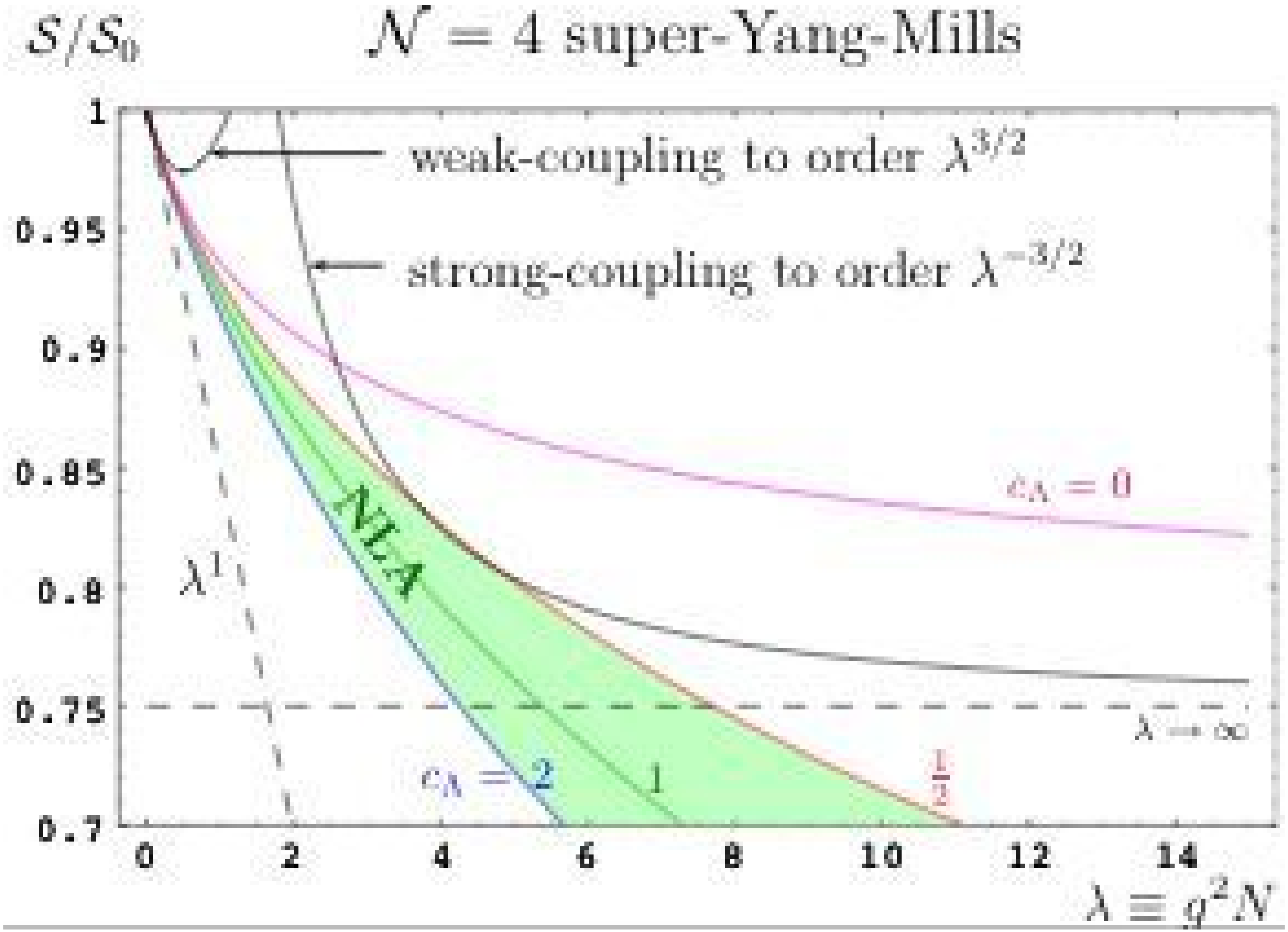
N=4 SYM in weak coupling

- Blaizot-Iancu-Rebhan treat s (entropy density) in N=4 SYM in weak coupling, then adjust ‘t Hooft coupling to match lattice data
- Old Gubser-Klebanov strong coupling result is: $s/s_{SB}=3/4+c/\lambda^{3/2}$, where c is a known number.
- Compare strong and weak coupling. They agree at λ which is stronger than that required to explain the data for $T>3T_c$
- Small window in T left for agreement with N=4 SYM with $N_c=\infty$ (too close to T_c the mass scale spoils conformal symmetry: lattice data)

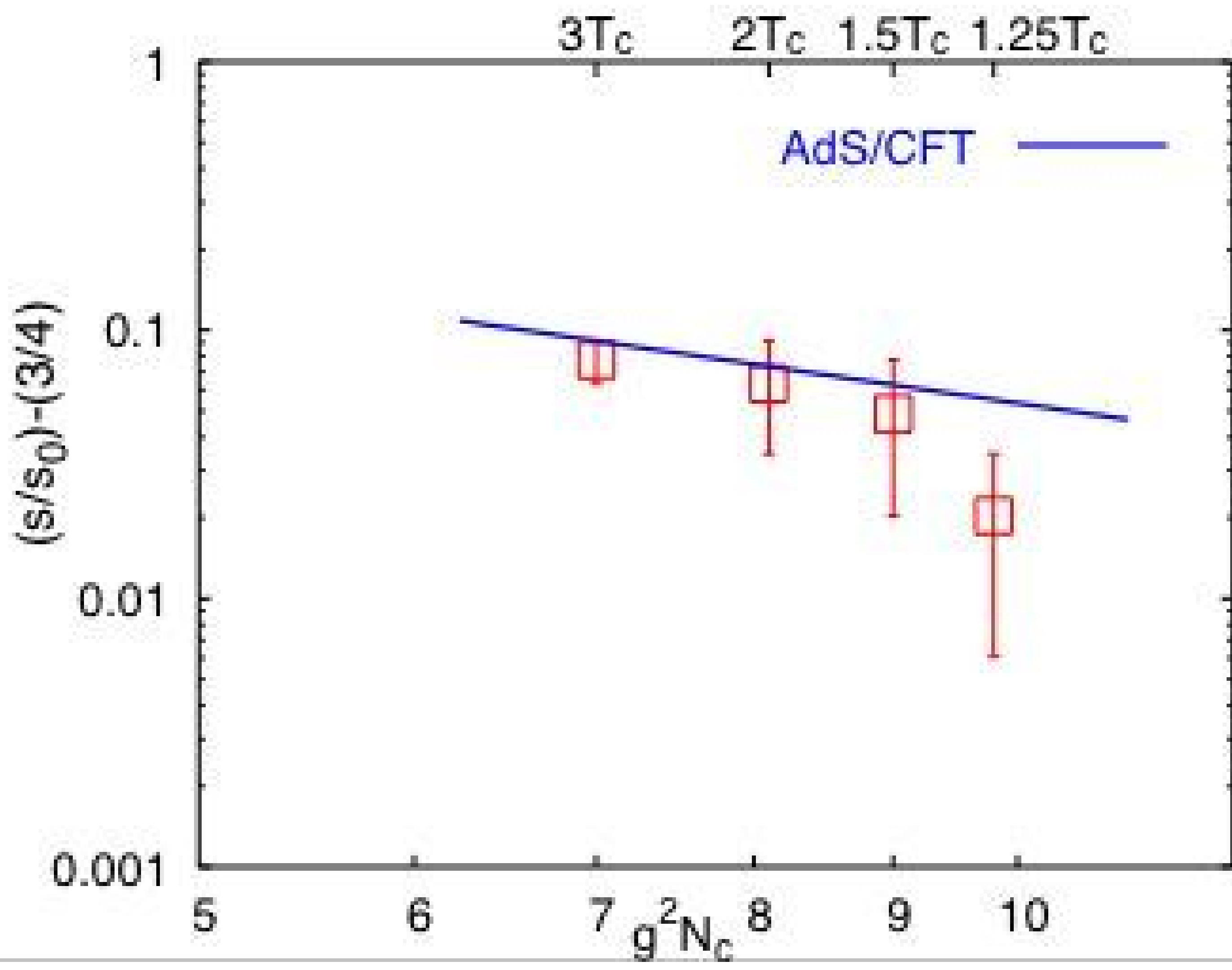
N=4 SYM in weak coupling



N=4 SYM in weak coupling



N=4 SYM in strong coupling



Mumbai: hep-lat/0506015

Conclusions

- N_f=2 QCD under reasonable control. **No phase transition for m>0 and μ=0.** Crossover temperature T_c fixed within 10%. **First estimates of QCD critical point available.**
- N_f=2+1 QCD under investigation. **T_c fixed within 10%.** Phase diagram constrained by deF&P as well as known results on N_f=2 QCD because **order parameter of N_f=2 QCD is also an order parameter of N_f=2+1 QCD**. Global constraints on flag diagram forces critical point for μ>0.
- **Quarks are liberated!** First direct proof.
- **EOS under control.** Window for AdS/CFT (strong coupling computation) shrinking.