Warm QCD

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TIFR Mumbai

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The standard model of heavy-ion collisions

- One reason to worry about warm QCD
- Why warm QCD is important
- No need to worry about anything else

Hot QCD is understood, in any case

Warm QCD is a nice and hard problem

Conclusions

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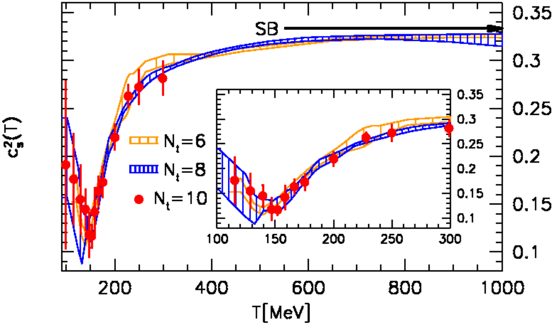
The QCD thermal cross-over

There is no phase transition in QCD at $\mu = 0$: gradual change from hadrons to quarks. Physically important: how fast does the fireball cool?



Endrodi et al, arxiv:1007.2580

Warm matter: 130 MeV$\leq T \leq$ 200 MeV, ie, $T \simeq m_\pi$

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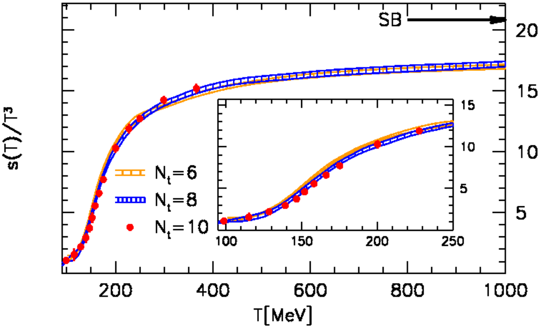

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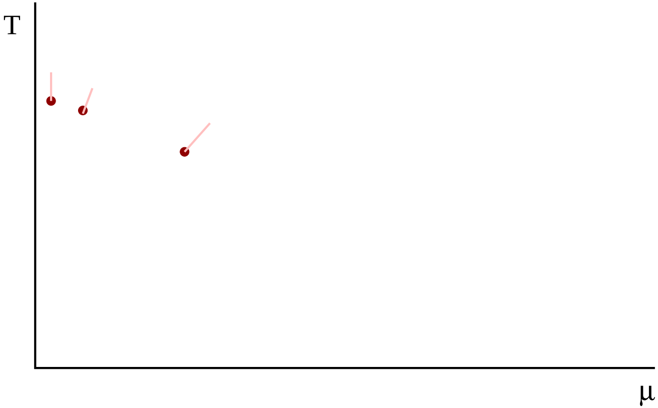
Systematics

Final state is observable and nearly thermal. So initial state is largely unknown, possibly far off equilibrium; evolution badly constrained (but jets, vector bosons).

Braun-Munzinger, Stachel, Cleymans, Redlich, Becattini

Systematics



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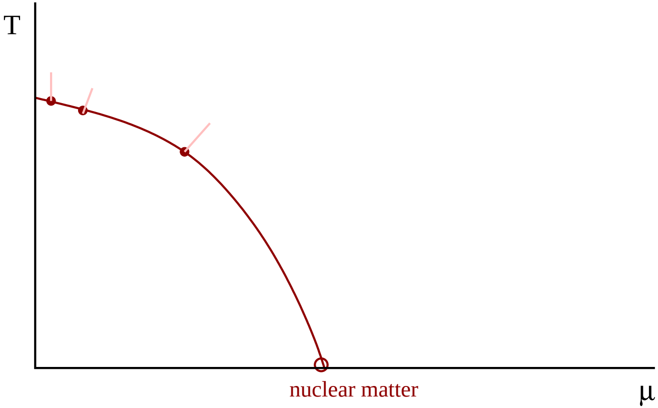

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What is the final state?

If there is a freezeout temperature, T, then it must depend on the typical hadronic cross section, σ and the typical mass m.
The mean free path is $\lambda \simeq 1/(\sigma\rho)$. In the non-relativistic limit $\rho \simeq \epsilon/m$, where ϵ is the energy density. So $\lambda \simeq m/(\sigma\epsilon)$.
The expansion rate is $\theta \simeq \dot{V}/V$, where V is the volume of the fireball. When $\lambda\theta \simeq 1$ the particles will no longer be in thermal equilibrium.
So, thermal freezeout will occur at time

$$\frac{1}{\theta_f} \simeq \frac{m}{\sigma\epsilon}.$$

Taking $1/\theta_f = 15$ fm, $m = 1$ GeV, $\sigma = 1$ fm^2 and setting $\epsilon \simeq T_f^4$, we find $T_f \simeq 150$ MeV. This is close enough to reality that one might want to think of a detailed dynamical model.

transport models

When does chemistry freeze out?

Basic observables are the spectra of identified particles; from this one gets yields. Relative yields of hadrons is the outcome of "chemistry".

Chemical freezeout conditions follow from arguments similar to before. Main change: chemistry requires inelastic cross sections. Since $\sigma_{in} < \sigma_{tot}$, therefore chemical freezeout occurs earlier than kinetic freezeout.

At earlier times, fireball is a reactive fluid: requires coupling of hydrodynamics with diffusion and flavour chemistry. Reaction rates depend on local densities as well as rates of mixing. Mixing controlled by advection (stirring) and diffusion. Need to understand the relative importance of the two effects.

What brings particles together?

Flavour chemistry changes due to reactions controlled by densities and diffusion or mixing. Which is more important is controlled by Peclet's number

$$\mathrm{Pe} = \frac{Lv}{D} = \frac{Lv}{\xi c_s} = \left(\frac{L}{\xi}\right) M.$$

When $\mathrm{Pe} \ll 1$ diffusion dominates; when $\mathrm{Pe} \gg 1$ it is mixing.
Crossover regime when $\mathrm{Pe} \simeq 1$.
New length scale: defines when advection becomes comparable to diffusion—

$$L \simeq \frac{\xi}{M}.$$

Since the flow has $M \leq \sqrt{3}$, for baryons, $L \simeq 0.3$ fm and for strange particles, $L \simeq 0.5$ fm. So over most of the history of the fireball chemistry is governed by diffusion.

Bhalerao and SG, 2009

Delayed freezeout

The rates for processes $p + \pi^- \leftrightarrow n + \pi^0$, remain high at $\simeq 100$ MeV, because $m_n - m_p$ is small and the yield of pions is large. So the chemical freezeout of unstrange baryon isospin can be delayed.

In the warm fireball, pion densities are $\rho_\pi \simeq (m_\pi T)^{3/2}$. The nucleon density is $\rho_N \simeq (m_N T)^{3/2} \exp(-m_N/T)$. The ratio is

$$\frac{\rho_N}{\rho_\pi} \simeq \left(\frac{m_N}{m_\pi}\right)^3 \exp\left(-\frac{m_N}{m_\pi}\right) \simeq 0.06$$

So the nucleons exist in a isospin bath of pions.

The $p \leftrightarrow n$ reaction proceeds without suppression right up to kinetic freezeout.

See however, BES scan: talk by Bedanga Mohanty

Early stages of the fireball

Most information inferred from models. Main tool is hydrodynamics. Requires equation of state: supplied by lattice QCD. Requires viscosities: suggested by SYM in the AdS/CFT correspondence.

General consensus: hot initial state with early thermalization works. Evolution by hydro using $\eta \simeq$2–3$S/(4\pi)$ with EoS close to that found in lattice QCD can yield final state observables. Unknowns: initial state, $\eta(T)$, $\zeta(T)$, hadronization after T_c, ... Extracted from data, and reasonable guesses when observables not clear.

Corroborating evidence: vector bosons and jets from the early stages. $T_\gamma \simeq 300$ MeV at RHIC; 500 MeV at LHC.

RHIC white papers, Nucl. Phys. A 757, 2005

Jetty reheating

There are other conceivable scenarios. If there is freezeout well above T_c, then mutually weakly interacting quarks and gluons must propagate through the QCD vacuum. This would pull out pairs from the vacuum and create multiple jet-like structures. Freezeout at temperature $T_f > T_c$ would give rise to minijets. Number of minijets is proportional to the entropy, $n_j \simeq VS(T_f) \simeq (RT_f)^3$: possibly large. Minijets could combine to give a secondary nearly thermal fireball— reheating.

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ATLAS (and later CMS, ALICE) observed elliptic flow in high multiplicity pp events. Plasma fireball not expected. Could this be minijets reheating?

Hard calculation: transport coefficients near and above T_c; gives λ in the QCD plasma phase. Alternatively, hard look at the phenomenology: what distinguishes orthodox from jetty reheating?

Jetty reheating cannot be dismissed out of hand

What about elliptic flow?

Biggest reason for this scenario: why elliptic flow in high multiplicity pp collisions? Explanation cannot be due to formation of a QGP fireball. Whatever explanation works in pp can be transferred to AA. Partonic collectivity natural.

What about jet quenching?

Interactions of jet and minijet could give rise to jet quenching. Process not very different from non-linear BFKL evolution for coloured glass condensate, except now applied to final state fragmentation function.

RHIC white papers, Nucl. Phys. A 757, 2005

A test of jetty reheating

In the standard model of HIC, baryon number, B, is initially only produced at very small rapidity. Typical x_{Bj} of valence quarks is about 0.2, so $\Delta y \simeq 0.2$. Then B is advected out for time $\tau \simeq 0.3$. Beyond this, it diffuses, so Δy does not increase. So the baryon distribution is restricted to $\Delta y \leq 0.5$.

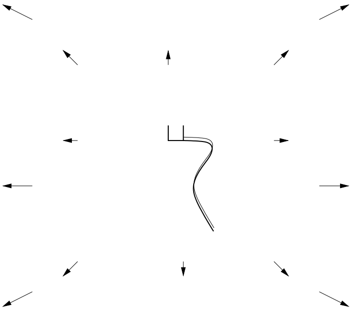
In jetty reheating, the spatial distribution of baryon number in the reheating stage is not connected to the baryon number in the initial stage. So, there can be significant baryon number at large y. The baryon density at large y is controlled by the baryon/meson ratio in fragmentation of jets.

Event-to-event distribution of baryon number can be found by studying the Fourier amplitudes of $B(y)$, and constructing its power spectrum.

The power spectrum of baryon number

Bhalerao and SG, 2009

The power spectrum of baryon number



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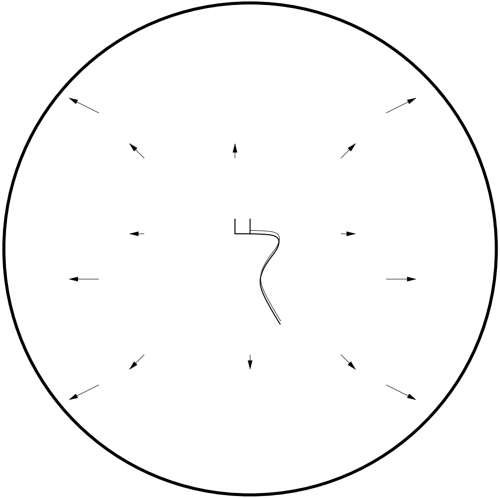

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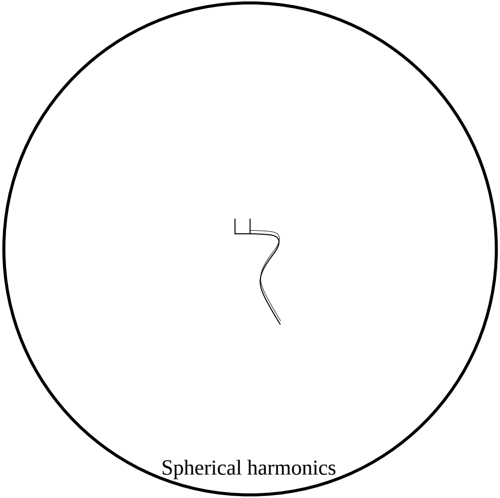

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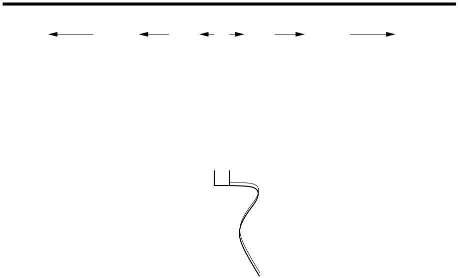

Bhalerao and SG, 2009

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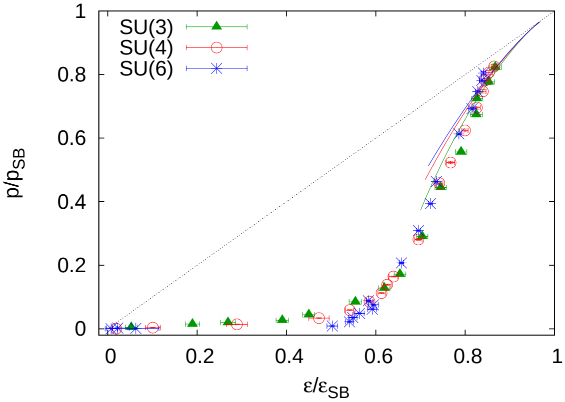
Fourier modes

Bhalerao and SG, 2009

Outline

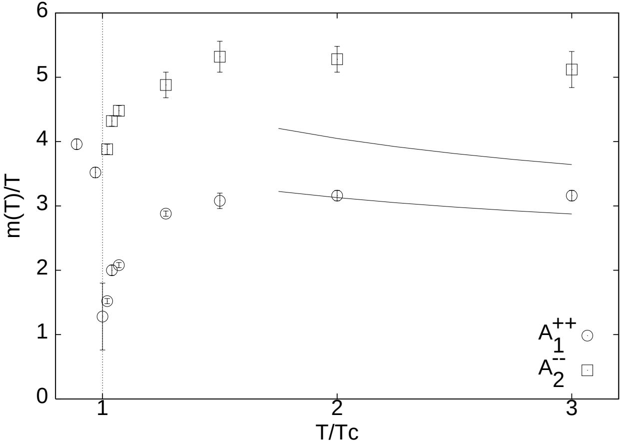
Equation of state: pure gauge theory



Laine and Schroeder, 2006; Saumen Datta and SG, 2011

Large departure from conformality: due to latent heat. EOS at $T > 2T_c$ quantitatively well understood. $N_f = 2$ less tested.

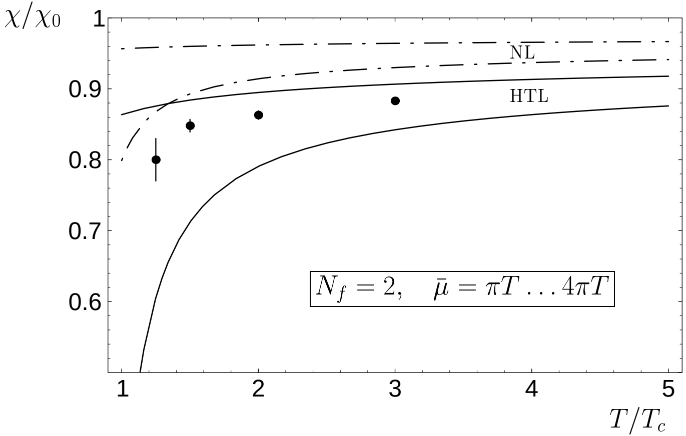
Gluonic correlations



Kajantie et al, 1997; Saumen Datta and SG, 2002

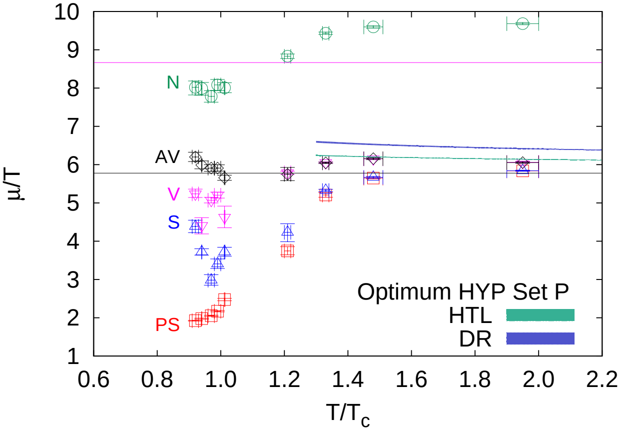
Error in weak-coupling resummation descends from error in α_s.

Quark number susceptibilities



Gavai, SG, Majumdar, 2000; Blaizot, Iancu, Rebhan, 2001.

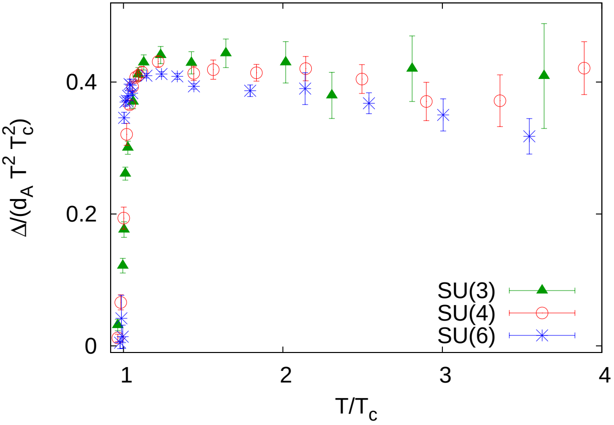
Fermionic correlations



Laine and Vepsäläinen, 2004; Alberico et al, 2007; Nikhil Karthik and SG, 2013

14% difference between two weak-coupling resummations.

Pisarski scaling



Saumen Datta and SG, 2011

Spontaneous mass generation in pure glue theory.

Weak coupling resummations

Thermodynamics at finite T is a multiscale problem, when the gauge coupling, g, is small.

1. The hard scale is T. Weak coupling theory at momentum scales, $p \geq T$ can be dealt with in perturbation theory: Feynman diagrams.
2. The scale gT is a soft scale. Infinite classes of Feynman diagrams need to be resummed if they involve $gT < p < T$. This is the HTL resummation. Can be rewritten as a kinetic theory.
3. The scale g^2T is a super-soft scale. All Feynman diagrams need to be resummed if they involve $g^2T < p < gT$. Better dealt with as an effective theory with some couplings matched non-perturbatively: lattice QCD computations needed. This is the DR framework.

In warm QCD $g \simeq 1$, although α_s may be small.

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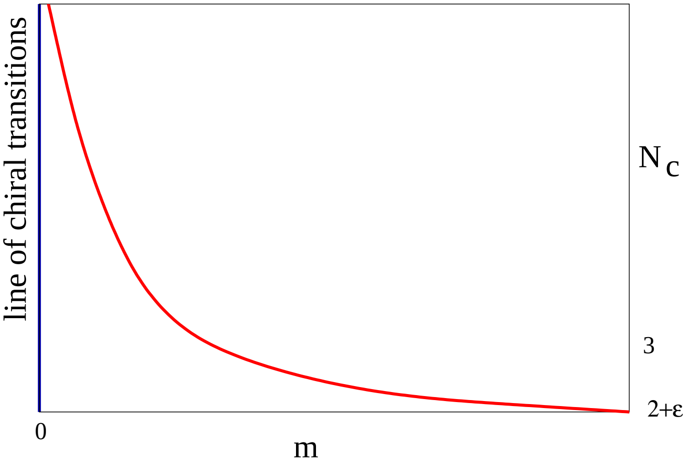
Flag diagram of gluoN_c plasmas



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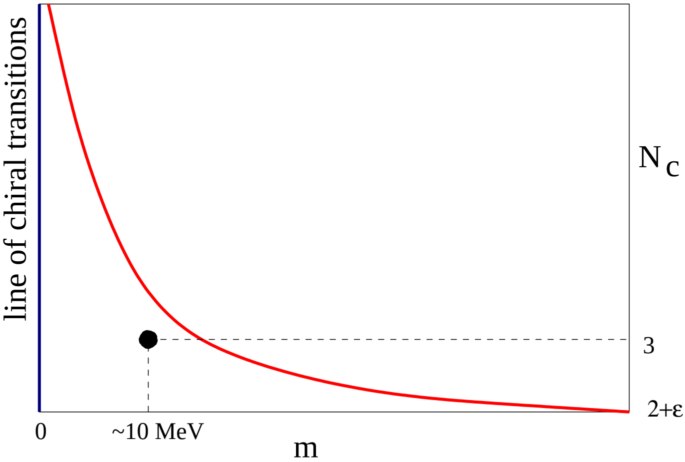

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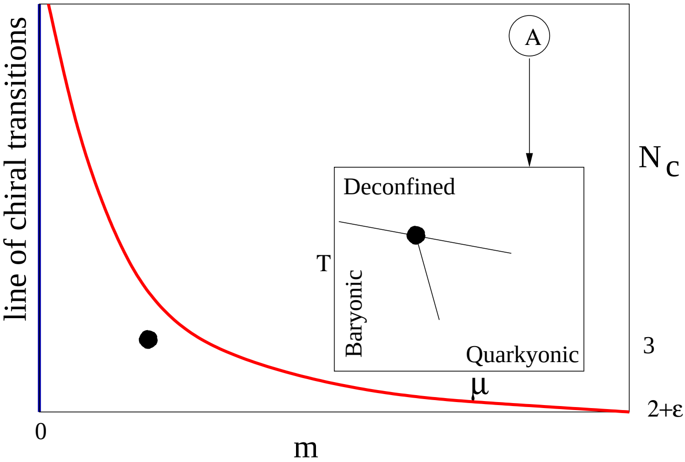

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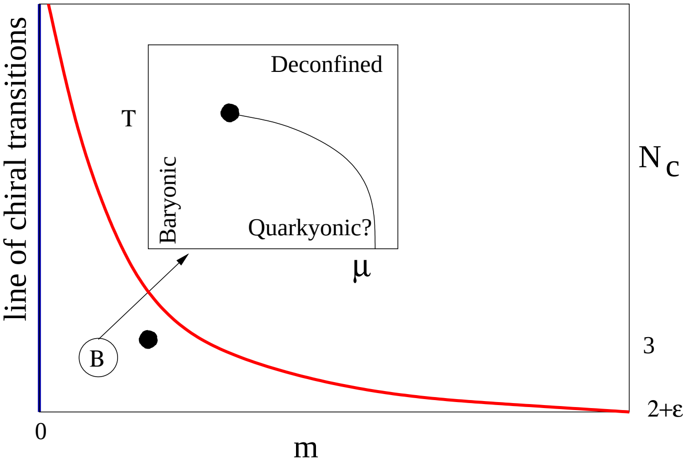
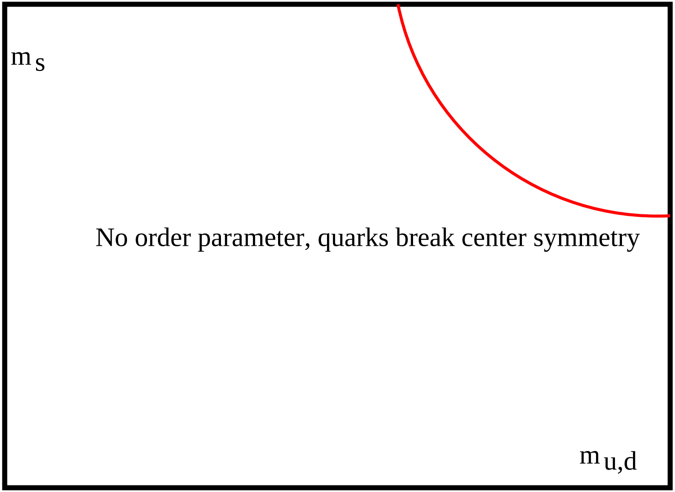


Large N_c does not capture phase diagram, but could suggest interesting hot or warm physics

Caveat



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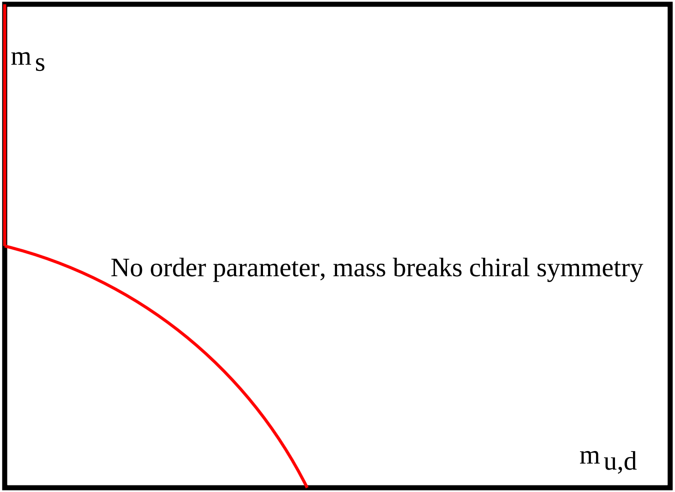

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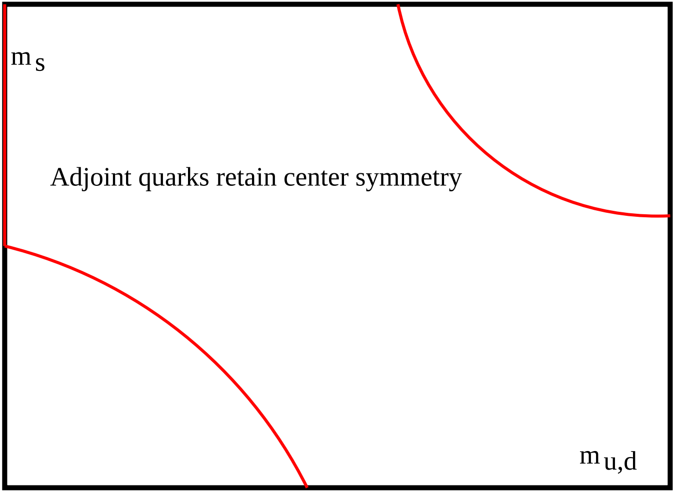
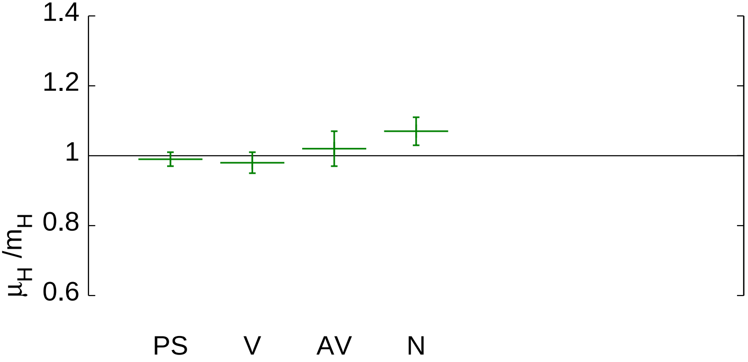


Adjoint quarks may distort findings

Cold screening masses



Padmanath, Datta, SG, Mathur, 2012: quenched QCD

Improved Wilson quarks with heavy pion ($m_\pi \simeq 2T_c$).

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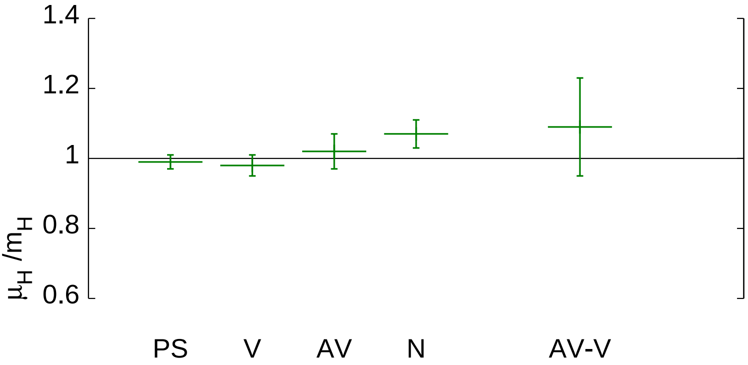

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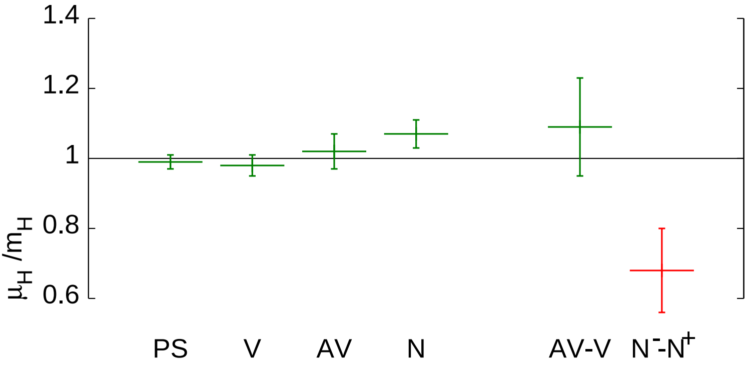

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Improved Wilson quarks with heavy pion ($m_\pi \simeq 2T_c$). Shift in nucleon sector mass splitting persists when pion mass decreases

Detailed models of freezeout

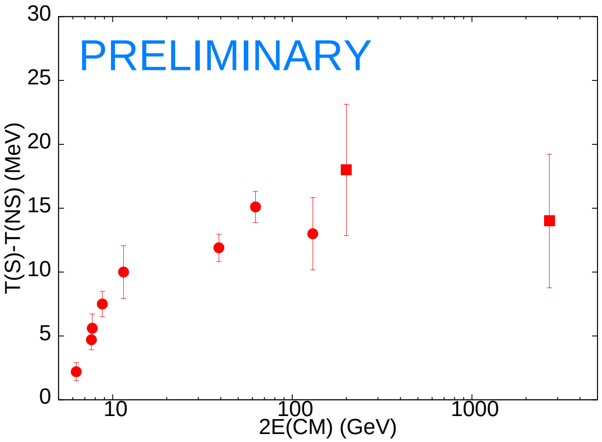
Freezeout parameters are obtained from data by fitting yields to parameters temperature, T, chemical potentials, μ, and interaction volume, V. Models in use till now involve a single freezeout point for every kind of particle. Very successful in many ways.

However, clearly an approximation, since detailed reaction dynamics should govern these parameters: example of delayed chemical freezeout of isobars in non-strange sector already given. Change in nucleon spectrum in warm QCD may also be important in similar way.

First attempt to fit different freezeout parameters to strange and non-strange sectors very successful, and seems to give interesting systematic results.

Sandeep Chatterjee, Godbole, SG, in progress

Differential freezeout model



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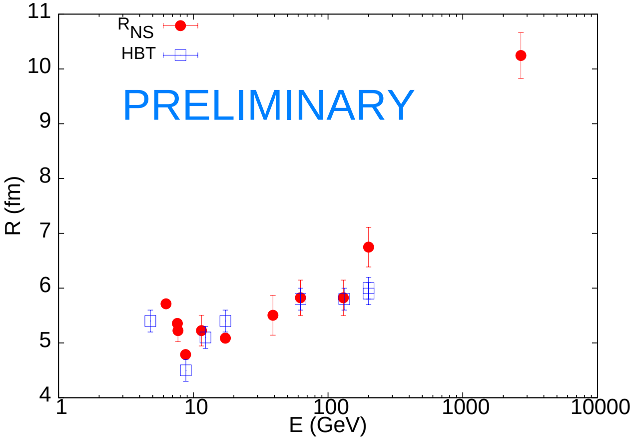

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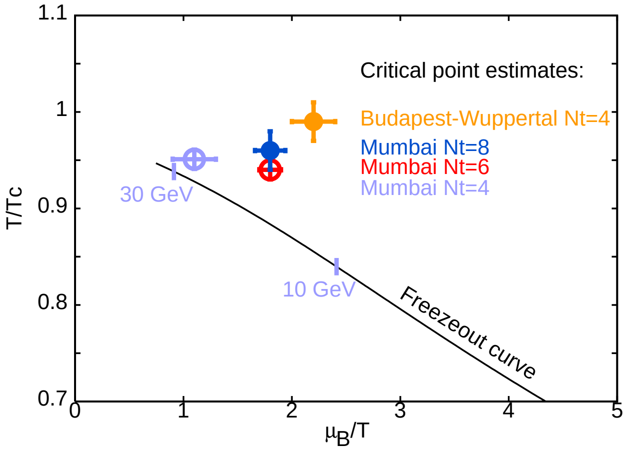
The critical end point of QCD



Datta, Gavai, SG, 2012

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Questions and conjectures

- The final state at freezeout contributes most of the observables in heavy-ion experiments. Freezeout takes place well below temperatures where a quark-gluon fluid is a good approximation. Flavour and hadron physics dominates observables: many scales, finely graded physics. Domain of warm QCD.
- Heavy-ion collisions give limited information on early stages of evolution. Standard model of uniformly cooling fireball. However, jetty reheating also possible: first freezeout in the high temperature phase, gluons and quarks propagate through the normal vacuum giving high density of minijets which re-interact and thermalize.
- Warm QCD is interesting. Hadron properties may be strongly modified close to T_c. Do complex hadron gas models work? Are multiple freezeout points important? Is there a good theoretical model? Is large N_c useful without large N_f?