

# Phases of baryonic matter

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December 17, 2010

# Outline

## Background

Experiments test non-perturbative QCD in bulk

- Theoretical developments

- Observational tests

The phase diagram of QCD

- Symmetry arguments

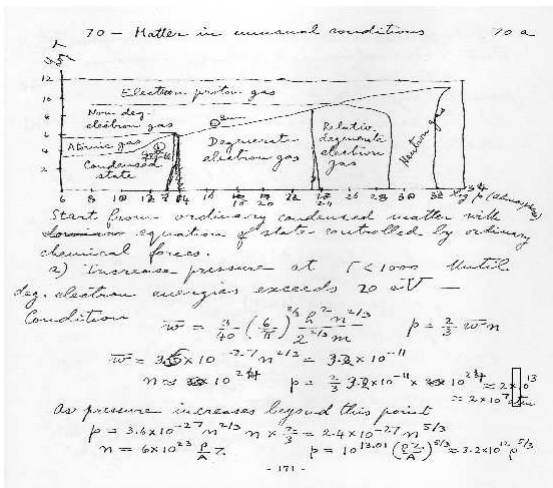
- Dynamics: lattice results

- Signal of the critical point

## Summary

## The forms of matter: an old quest

Enrico Fermi: notebooks



# Extreme matter today

QCD: theory of strong interactions

SU(3) gauge theory of interacting quarks and gluons. Theory of gluons classically scale free, quantum corrections generate a scale:  $\Lambda_{QCD}$ .

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SU(3) gauge theory of interacting quarks and gluons. Theory of gluons classically scale free, quantum corrections generate a scale:  $\Lambda_{QCD}$ .

A theorist's reflex

Given Hamiltonian compute eigenstates, S-matrix elements: talk by Gottlieb, others.

Compute physics in a heat-bath:  $Z(T, \mu) = \text{Tr} \exp[-\beta(H - \mu B)]$ .  
Thermodynamics and phase transitions etc.

# The experimental reflex



" We didn't have flint when I was a kid, we had to rub two sticks together. "

# The set of questions

Can experiment test any non-perturbative predictions of QCD?

In heavy-ion collisions QCD often enters indirectly: as the result of a long secondary computation such as hydro. Instead, can one get directly at QCD?

Can experiment test the existence of a critical point of QCD?

Do heavy-ion experiments have anything to say about the phase diagram? Or are they just dirtier versions of proton-proton collisions?

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## Non-linear susceptibilities

Taylor expansion of the pressure in  $\mu_B$

$$P(T, \mu_B + \Delta\mu_B)/T^4 = \sum_n \frac{1}{n!} \left[ \chi^{(n)}(T, \mu_B) T^{n-4} \right] \left( \frac{\Delta\mu_B}{T} \right)^n$$

has Taylor coefficients called **non-linear susceptibilities (NLS)**.

When  $\mu_B = 0$  they can be computed directly on the lattice, otherwise reconstructed from such computations.

(Gavai, SG: 2003, 2010)

Cumulants of the event-to-event distribution of baryon number are directly related to the NLS:

$$[B^2] = T^3 V \left( \frac{\chi^{(2)}}{T^2} \right), \quad [B^3] = T^3 V \left( \frac{\chi^{(3)}}{T} \right), \quad [B^4] = T^3 V \chi^{(4)}.$$

$V$  unknown, can be removed by taking ratios.

(SG: 2009)

# Tests and assumptions

$$m_1 : \frac{[B^3]}{[B^2]} = \frac{\chi^{(3)}(T, \mu_B)/T}{\chi^{(2)}(T, \mu_B)/T^2}$$

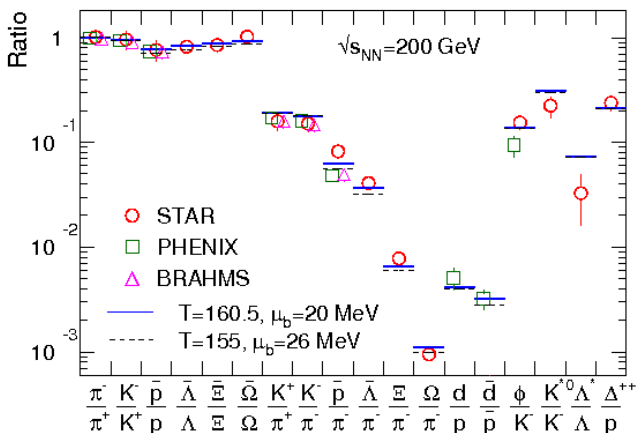
$$m_2 : \frac{[B^4]}{[B^2]} = \frac{\chi^{(4)}(T, \mu_B)}{\chi^{(2)}(T, \mu_B)/T^2}$$

$$m_3 : \frac{[B^4]}{[B^3]} = \frac{\chi^{(4)}(T, \mu_B)}{\chi^{(3)}(T, \mu_B)/T}$$

Also for cumulants of electric charge,  $Q$ , and strangeness,  $S$ .

1. Two sides of the equation equal if there is thermal equilibrium and no other sources of fluctuations.
2. Right hand side computed in the grand canonical ensemble (GCE). Can observations simulate a grand canonical ensemble? What  $T$  and  $\mu_B$ ?

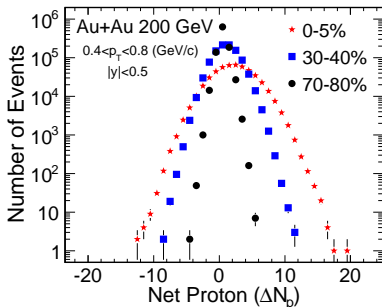
# The fireball thermalizes



Chemical freeze out:  $T = 160.5$  MeV,  $\mu = 20$  MeV.

Andronic et al, nucl-th/0511071

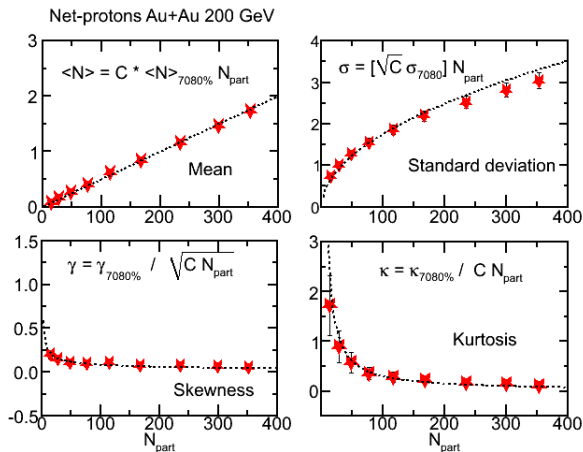
# Event distributions of conserved charges



- ▶ Fluctuations of conserved quantities are Gaussian: provided large volume and equilibrium
- ▶ Proton number a substitute for baryon number: how good?
- ▶ Is this Gaussian due (entirely or largely) to thermal fluctuations?

STAR, 1004.4959

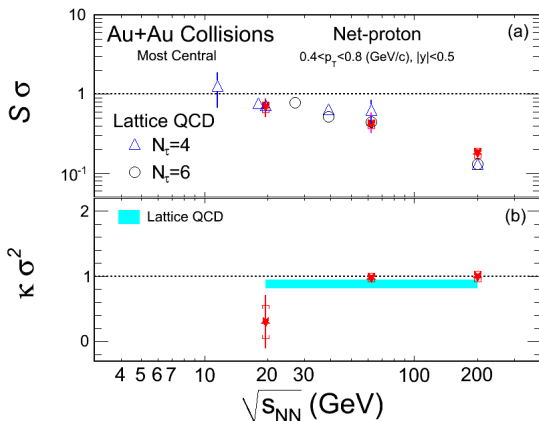
## STAR measurements: 2009



$l \gg \xi$  ( $K \ll 1$ ) tested and found true.

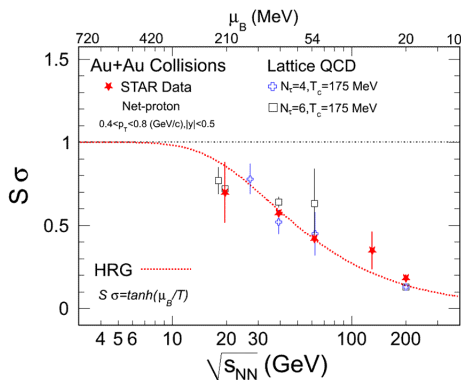
STAR Collaboration: QM 2009, Knoxville

## STAR measurements: beginning 2010



First ever agreement between lattice and experiment for bulk matter! STAR Collaboration: 2010

## STAR measurements: end 2010



Continuing agreement between bulk matter lattice and experiment!  
 STAR Collaboration: ICPAQGP, Goa, December 2010

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# How many flavours?

## Scales of masses

In QCD two quarks are almost chiral:  $m_{ud} \ll \Lambda_{QCD}$ .

One quark is medium heavy:  $m_s \simeq \Lambda_{QCD}$ .

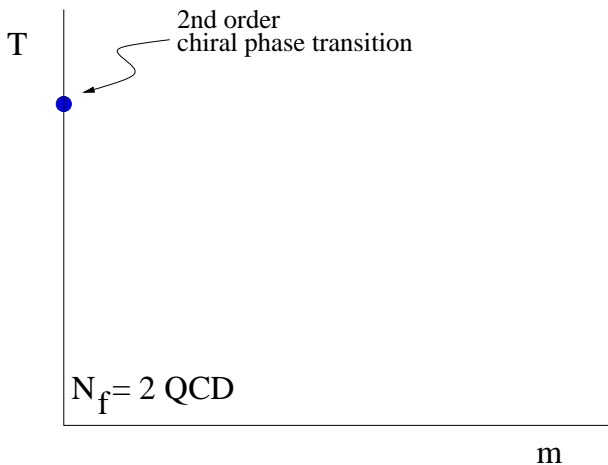
Three quarks decouple:  $m_{c,b,t} \gg \Lambda_{QCD}$ .

How light should  $m_s$  be to change the phase diagram?

If  $m_{uds}$  are simultaneously tuned from physical values then  $m_s$  must be decreased by factor of 6 or more. Endrodi etal, 0710.0988 (2007)

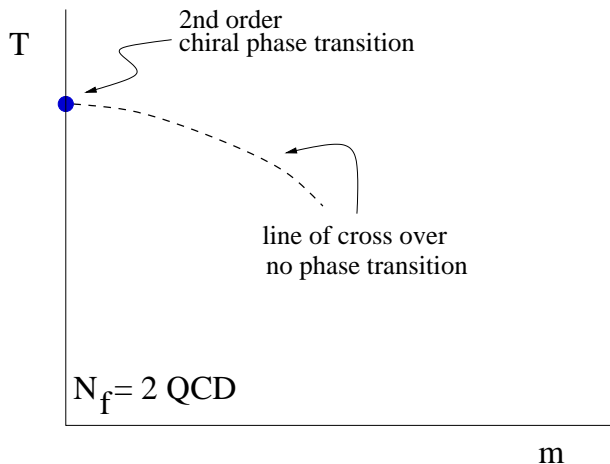
Similarly for  $N_f = 3$ . Karsch etal, hep-lat/0309121 (2004)  
 $N_f = 2$  phase diagram qualitatively fine.

# The $T = 0$ phase diagram



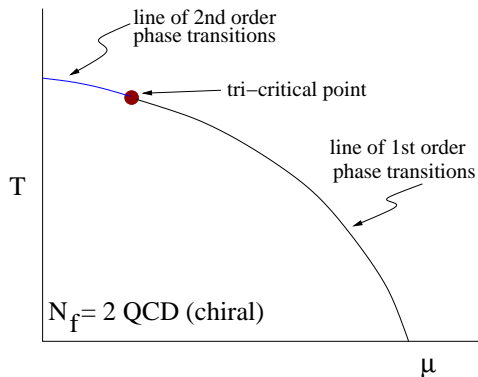
Phase diagram plots singularities of free energy.  
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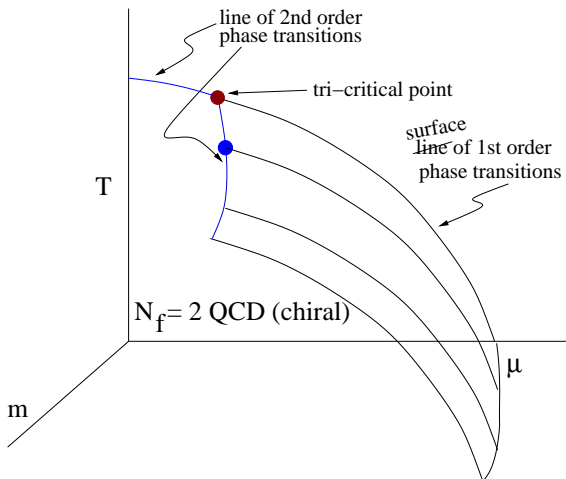
# The extended phase diagram



Rajagopal, Stephanov, Shuryak 1998 and 1999

Other effects: anomaly, large- $N$  counting, condensed phases?

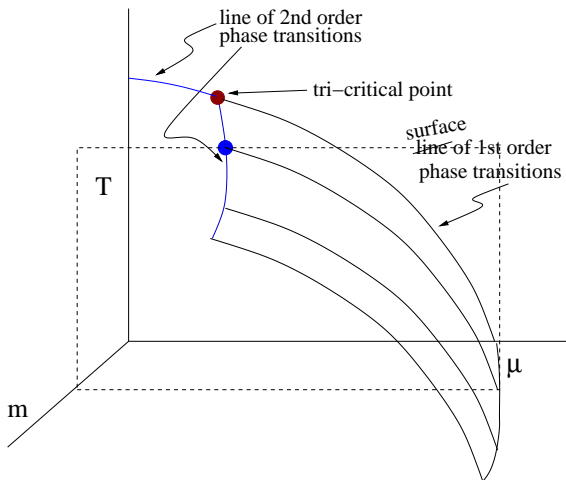
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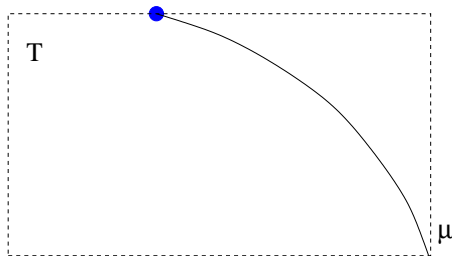
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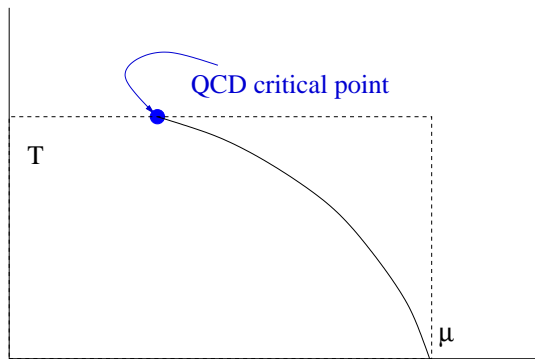
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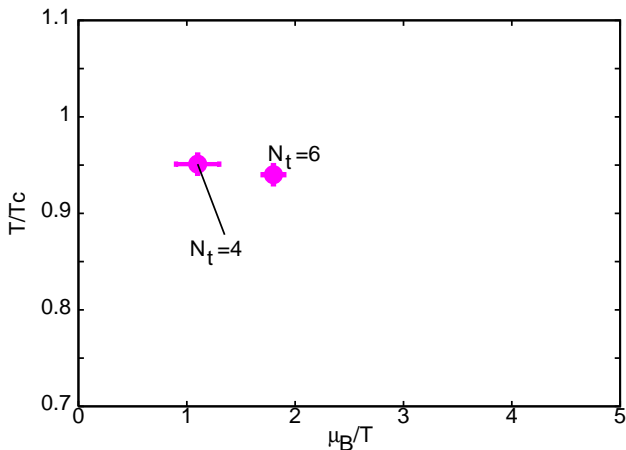
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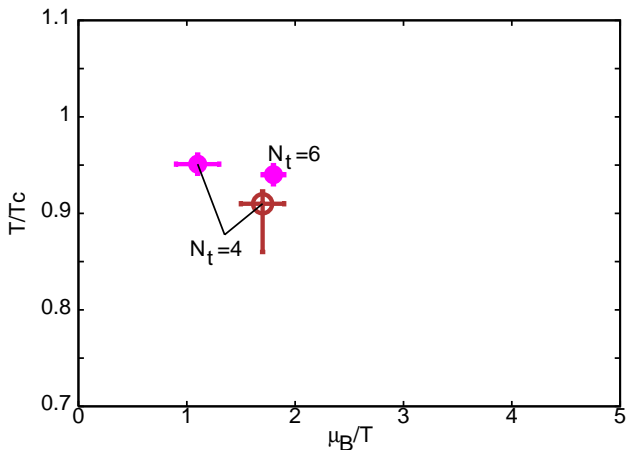
# The critical point from lattice QCD



Staggered:  $N_f = 2$ ,  $m_\pi = 230$  MeV,  $LT \geq 4$  Gavai, SG, 0806.2233

P4:  $N_f = 2 + 1$ ,  $m_\pi = 220$  MeV,  $LT = 4$  Schmidt, 2010

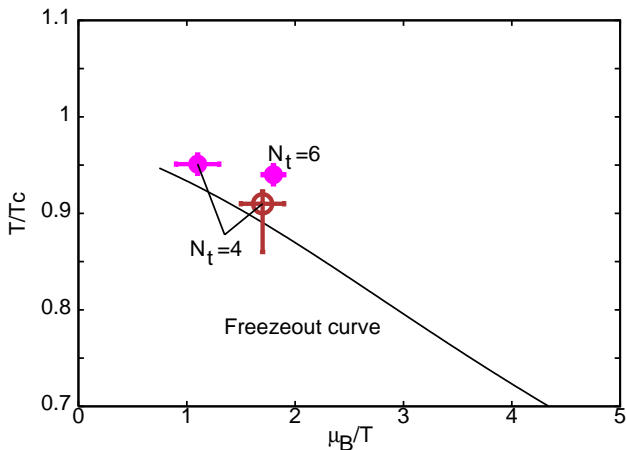
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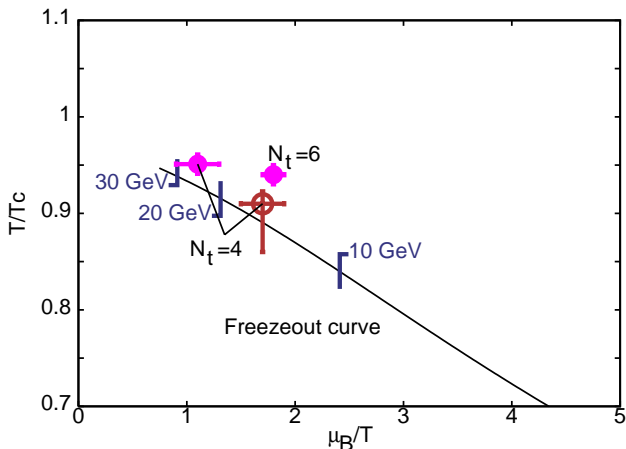
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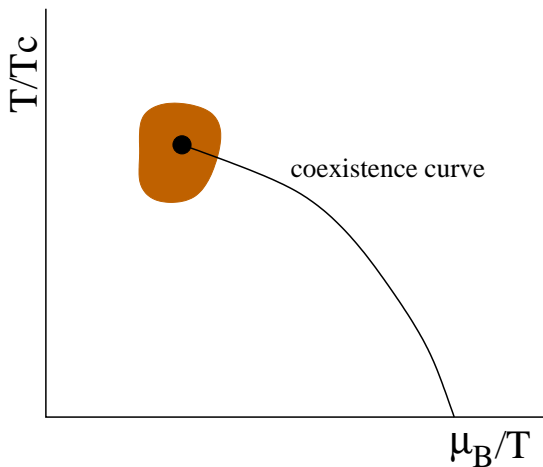
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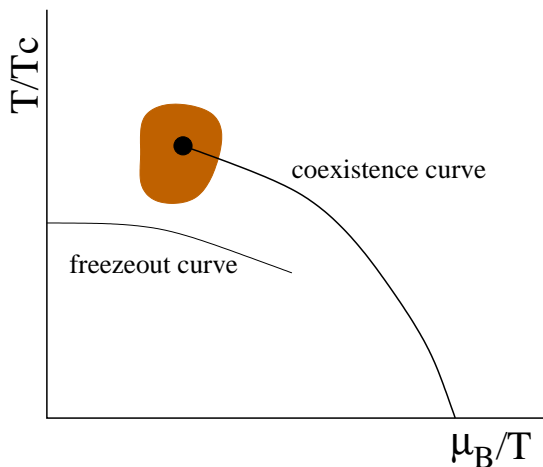


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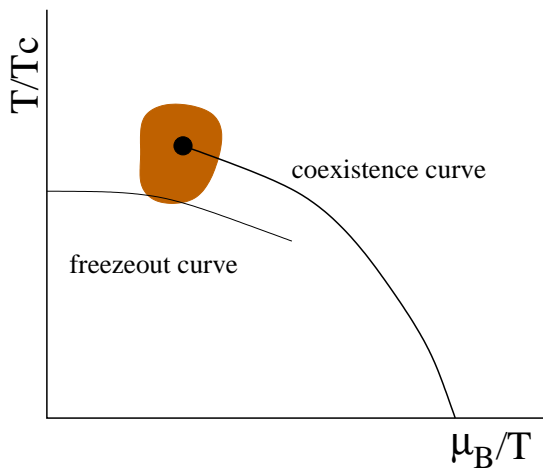
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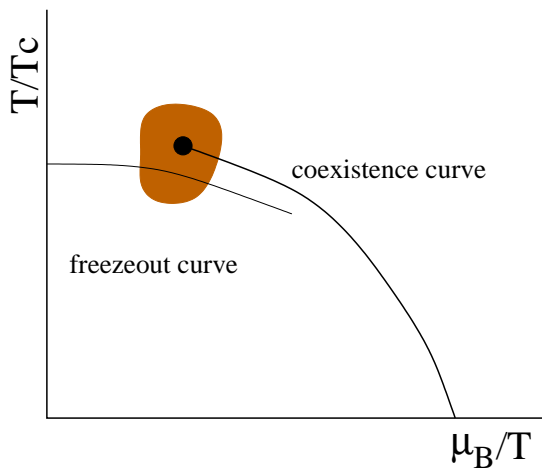
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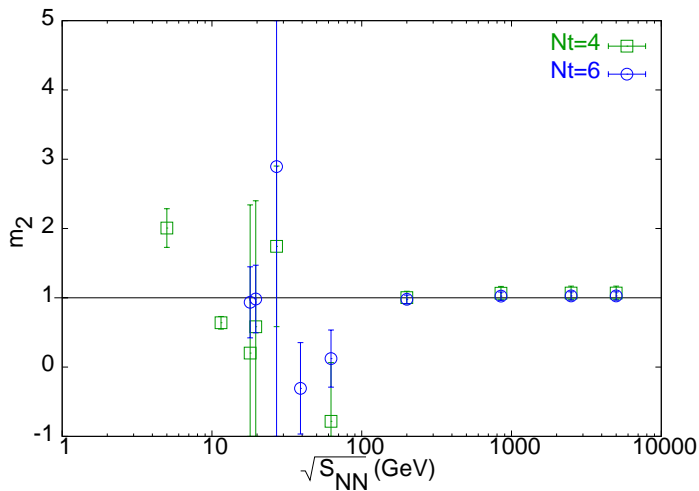
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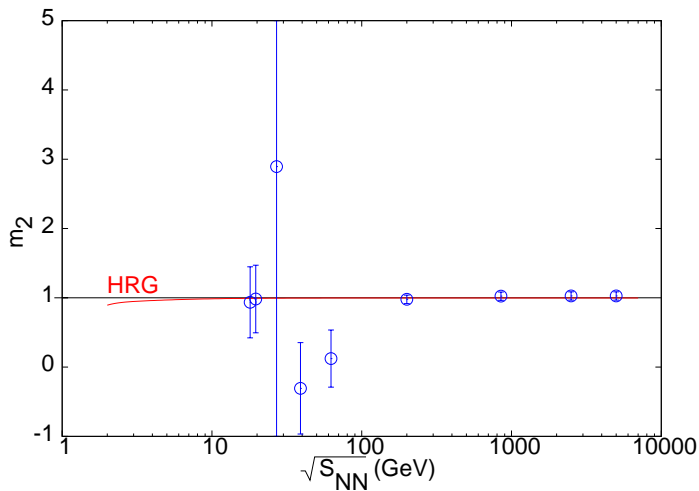


## Observables



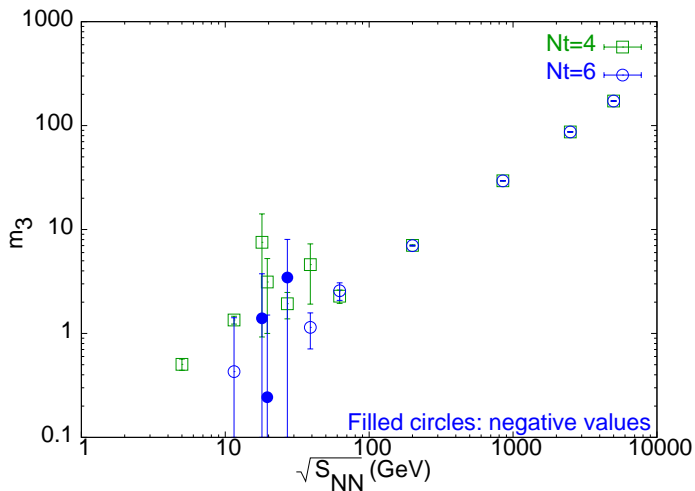
Gavai, SG: 2010

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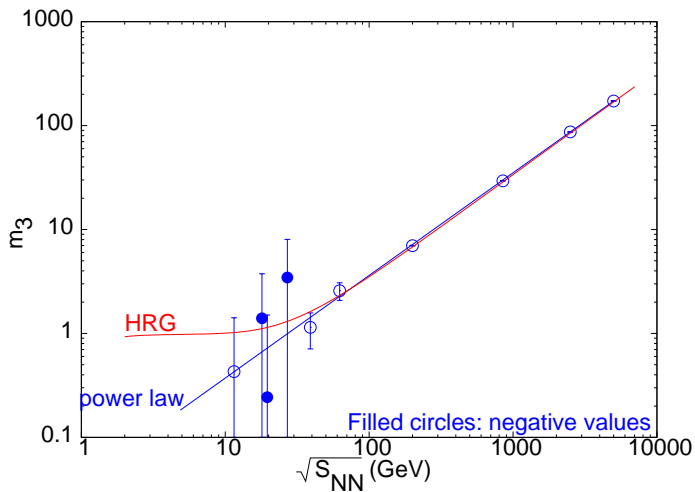
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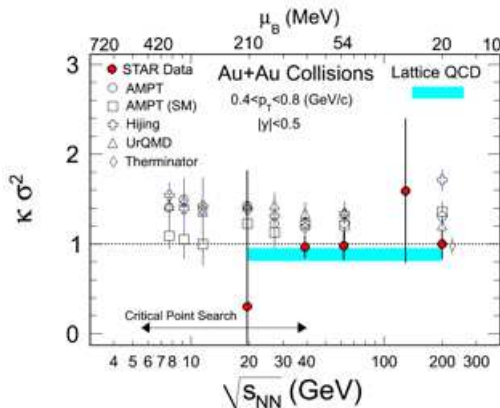
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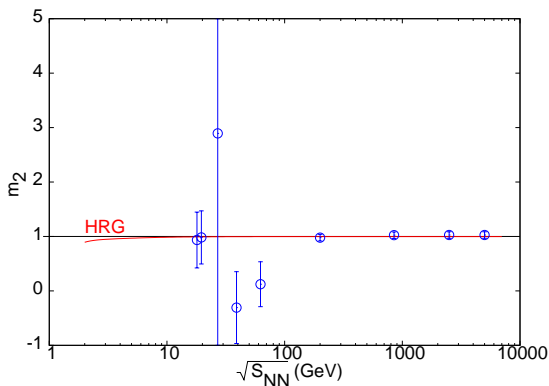
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## New STAR data



Intriguing structure in  $m_2$ : not predicted by models which have no critical point. See also PNJL: Deb (parallel session)

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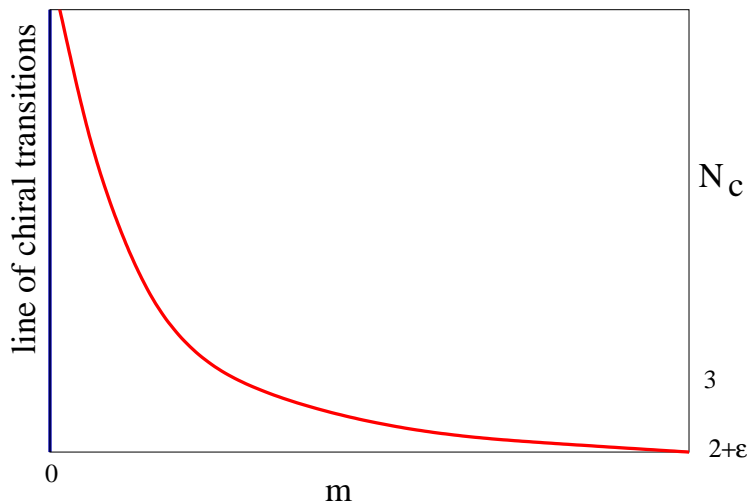
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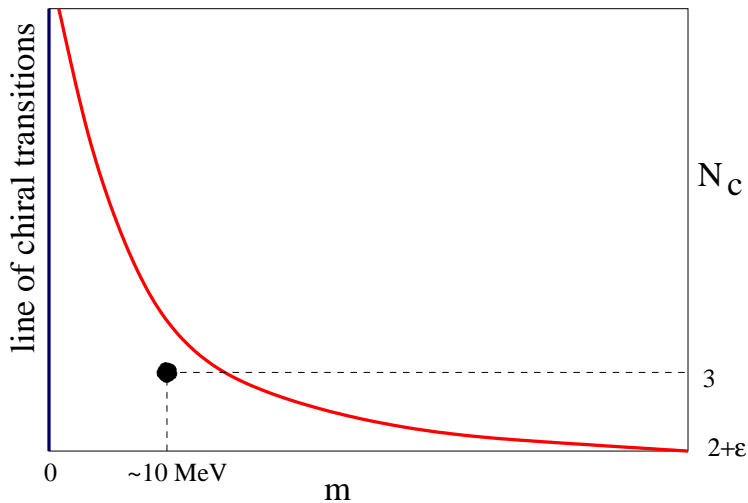
## The sign problem in QCD can be evaded

1. The strange quark is heavy; light quarks determine the shape of the phase diagram. The cross over temperature now under control:  $T_c \simeq 170$  MeV. SU(2) flavour symmetry breaking unlikely to change  $T_c$ .
2. Lattice determines series expansion of pressure; indicates a critical point in QCD. Lattice spacing effects under reasonable control. Physical quantities can be found by resumming the series expansion (e.g., Padé approximants).
3. First direct comparison of lattice results with experimental data done; good agreement. A landmark in the field: good evidence for thermalization.
4. A step-by-step analysis suggested for critical point: failure of CLT scaling, fluctuations not frozen at chemical freezeout, evidence for non-monotonic behaviour of  $m_{1,2,3}$  near this point.

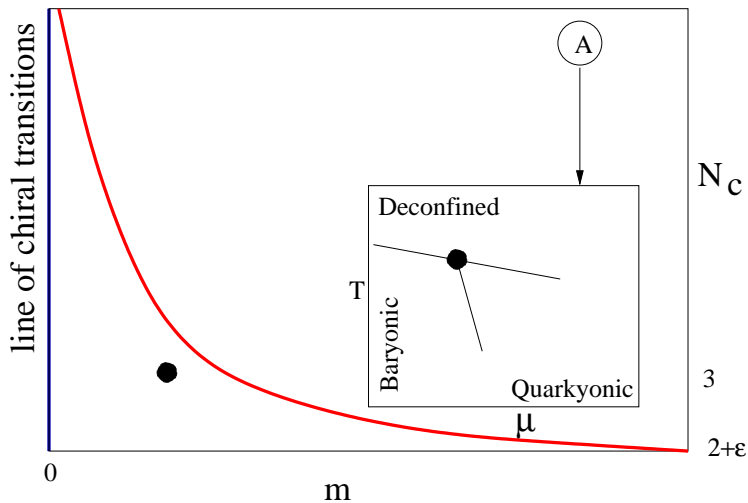
Have another  $N$ ? No thanks

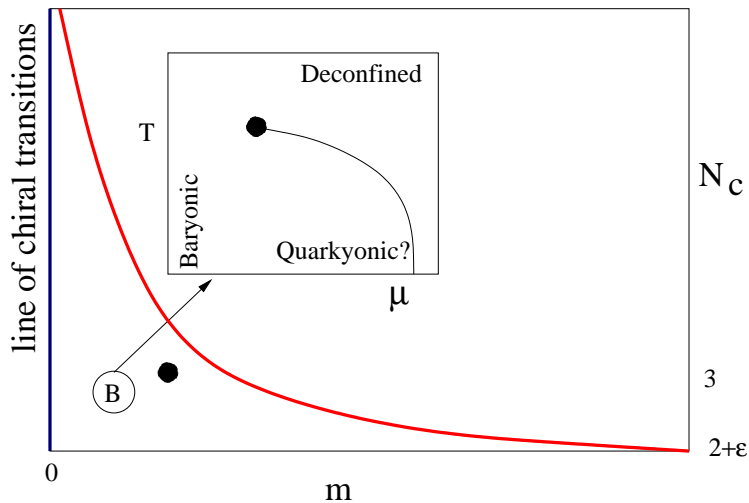


Have another  $N_c$ ? No thanks

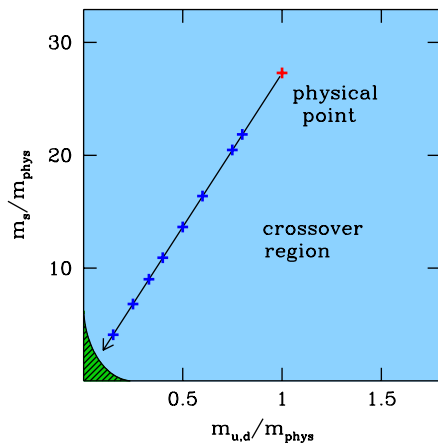


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## Lattice results for the Columbia Plot



In  $N_f = 2 + 1$ :

$$m_{\pi}^{crit} \begin{cases} = 0.07 m_{\pi} & (N_t = 4) \\ < 0.12 m_{\pi} & (N_t = 6) \end{cases}$$

Endrodi et al, 0710.0988  
(2007)

Similarly for  $N_f = 3$ .

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