# Quark Mass Dependence of the QCD Equation of State on $N_t = 8$ Lattices

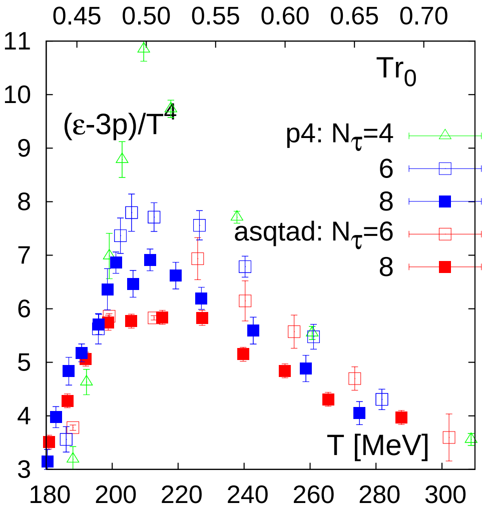
Wolfgang Söldner
RBC-Bielefeld and hotQCD Collaborations

BNL

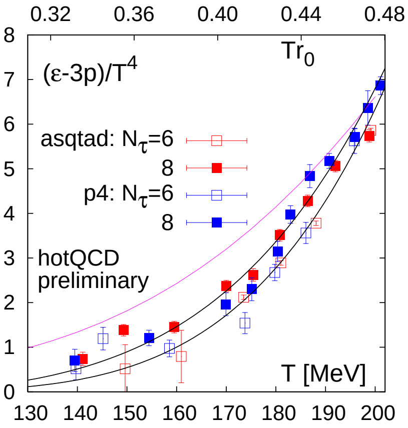
Lattice 2008

# Introduction

## QCD Equation of State (EoS) for $N_t = 8$



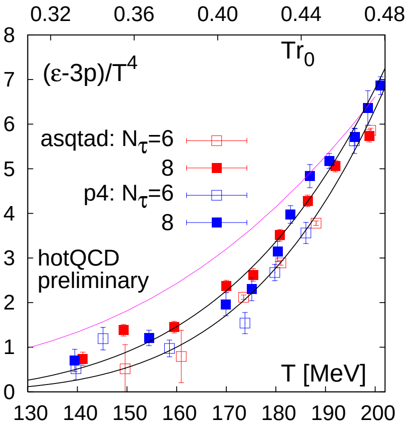
# QCD EoS for $N_t = 8$: Low Temperature Regime




## Hadron Resonance Gas Model (HRG)

- relativistic fermi and bose gas
- temperature excitations of stable massive hadrons
- interaction between stable particles described by resonance spectrum
- resonances up to $2.5 GeV$

# QCD EoS for $N_t = 8$: Low Temperature Regime




deviations from HRG model?

→ study quark mass dependence of equation of state

# Numerical Details

## QCD Lattice EoS

- p4fat3 action, RHMC algorithm
- calculate QCD trace anomaly ($\Theta^{\mu\mu} \equiv \varepsilon - 3p$) on the lattice
- subtract zero temperature part: $(\varepsilon - 3p)_T - (\varepsilon - 3p)_{T=0}$
- determine thermodynamic quantities, e.g. pressure $p$ by integration: $\Theta^{\mu\mu}/T^4 = T\partial/\partial T(p/T^4)$
  $\frac{p(T)}{T^4} - \frac{p(T_0)}{T_0^4} = \int_{T_0}^{T} \mathrm{d}\bar{T}\, \frac{1}{\bar{T}^5} \Theta^{\mu\mu}(\bar{T})$

→ large computational costs
supercomputers BG/L, BG/P, QCDOC
at Brookhaven (BNL), Jülich, Livermoore (LLNL)

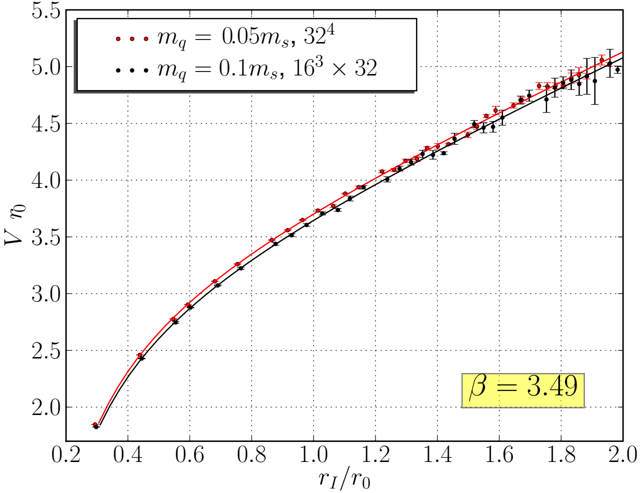
→ talk given by Rajan Gupta

# Set Up

## Simulation Details: $N_t = 8$

| | | |
|---|---|---|
| Masses: | $m_q = 0.1 m_s$ | $m_q = 0.00081 - 0.00370$ |
| | $m_q = 0.05 m_s$ | $m_q = 0.00120 - 0.00145$ |
| Pion Masses: | $m_q = 0.1 m_s$ | $m_\pi \approx 220 MeV$ |
| | $m_q = 0.05 m_s$ | $m_\pi \approx 160 MeV$ |
| Volume ($T \neq 0$): | $m_q = 0.1 m_s$ | $32^3 \times 8$ |
| | $m_q = 0.05 m_s$ | $32^3 \times 8$ |
| Volume ($T = 0$): | $m_q = 0.1 m_s$ | $32^4$ |
| | $m_q = 0.05 m_s$ | $32^4$ |
| Stats. ($T \neq 0$): | $m_q = 0.1 m_s$ | # 8,000-37,000 |
| | $m_q = 0.05 m_s$ | # 5,000-20,000 |
| Stats. ($T = 0$): | $m_q = 0.1 m_s$ | #2,000 - 6,000 |
| | $m_q = 0.05 m_s$ | # 1,500-2,000 |

# Potential ($\beta = 3.49$)



# Potential (preliminary)

Details: set $r_0 = 0.469\ fm$

| $\beta$ | 3.49 | 3.51 | 3.53 | 3.54 |
|---|---|---|---|---|
| $a_{m_q=0.1m_s}$ $[fm]$ | 0.1455 | 0.1370 | | 0.1272 |
| $a_{m_q=0.05m_s}$ $[fm]$ | 0.1435 | 0.1385 | 0.1306 | |
| $r_0\ _{m_q=0.1m_s}$ | 3.223(23) | 3.423(30) | | 3.689(37) |
| $r_0\ _{m_q=0.05m_s}$ | 3.2675(90) | 3.386(20) | 3.592(11) | |
| $T_{m_q=0.1m_s}$ $[MeV]$ | 169.5(1.2) | 180.0(1.6) | | 194.0(1.9) |
| $T_{m_q=0.05m_s}$ $[MeV]$ | 171.85(47) | 178.1(1.1) | 188.90(60) | |
| $\#_{m_q=0.1m_s}$ | 330 | 140 | | 300 |
| $\#_{m_q=0.05m_s}$ | 200 | 200 | 170 | |

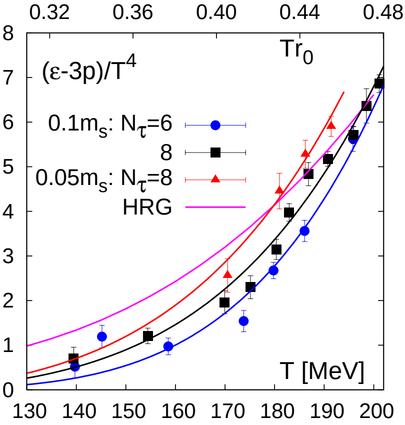
$\rightarrow$ Volume: $16^3 \times 32$, $m_q = 0.1 m_s$
$32^4$, $m_q = 0.05 m_s$

# Potential (preliminary)

## Scale: Results

- preliminary results, calculations ongoing
- within error bars scale consistent with $m_q = 0.1 m_s$
- for the moment:
  use global mass fit (more data points involved)
  $a_{m_q=0.05m_s} = \exp(-2A\,\Delta m_q)\, a_{m_q=0.1m_s}$
  with $A = 1.40(3)$
- $\rightarrow$ shift in temperature of about $0.5 MeV$

# Mass Dependence




## Comments:

- $T^2$ fit (lines)
- shift in T of about $4MeV$
- high T: consistent with HRG
- low T: no conclusion yet
  $\rightarrow$ more points necessary
  (calculations ongoing)

hotQCD and RBC-Bielefeld, preliminary

# Mass Dependence: Discussion

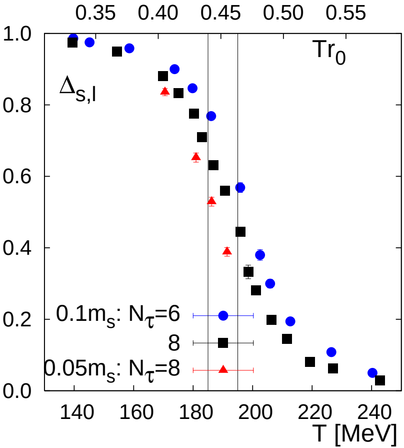
## Intermediate Temperature Regime

- for smaller light quark mass → shift to lower temperature
- almost physical pion mass (for $m_q = 0.05 m_s$)
- temperature shift in the scale →0.5 $MeV$
- total temperature shift $\approx 4 MeV$
  → consistent with shift in $T_c$

## Hadron Resonance Gas Model (HRG)

- for smaller light quark mass → closer to HRG EoS
- still deviations from HRG EoS (in the low T regime)

# Chiral Condensate: $\rightarrow$ talk by Frithjof Karsch




Definition: $\Delta_{l,s} = \frac{\langle\bar{\psi}\psi\rangle_{l,\tau} - \frac{\hat{m}_l}{\hat{m}_s}\langle\bar{\psi}\psi\rangle_{s,\tau}}{\langle\bar{\psi}\psi\rangle_{l,0} - \frac{\hat{m}_l}{\hat{m}_s}\langle\bar{\psi}\psi\rangle_{s,0}}$

- combination: cancel add. renormalization
- normalization by $T = 0$: cancel mult. renormalization factors

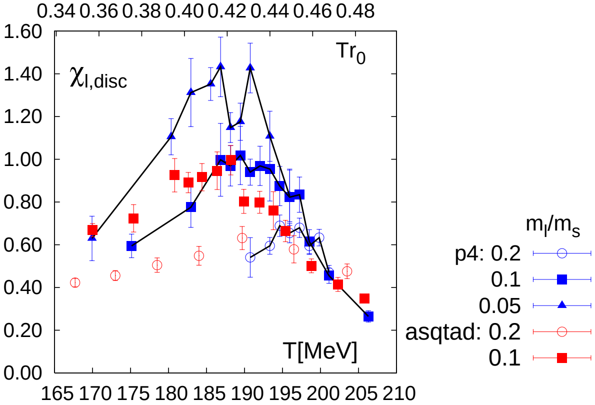
hotQCD and RBC-Bielefeld, preliminary

# Chiral Condensate: Discussion

## Details

- sharp drop in $\Delta_{l,s}$ for $m_q = 0.1 m_s$ and $m_q = 0.05 m_s$
- $m$ and $\sqrt{m}$ terms near $T_c$
  $\rightarrow$ 2 points not sufficient for $m \rightarrow 0$ extrapolation
- data analysis ongoing (also for $N_t = 4$)

# Chiral Susceptibility




- $T_c$ determination
- $\sqrt{m}$ behavior visible

hotQCD and RBC-Bielefeld, preliminary

# Summary

## Mass dependence EoS: temperature range close to $T_c$

- total shift in temperature of about $4 MeV$
- T close to $T_c$: consistent with HRG
- lower T: deviations from HRG $\rightarrow$ more data points necessary
- calculations ongoing

## Chiral Condensate: $\rightarrow$ talk by Frithjof Karsch

- sharp drop in $\Delta_{l,s}$ for $m_q = 0.1 m_s$ and $m_q = 0.05 m_s$
- calculations ongoing

## Chiral Susceptibility

- $\sqrt{m}$ behavior visible
- calculations ongoing