ウィルソンクォークを用いた $N_f=2+1$ QCD の状態方程式の研究

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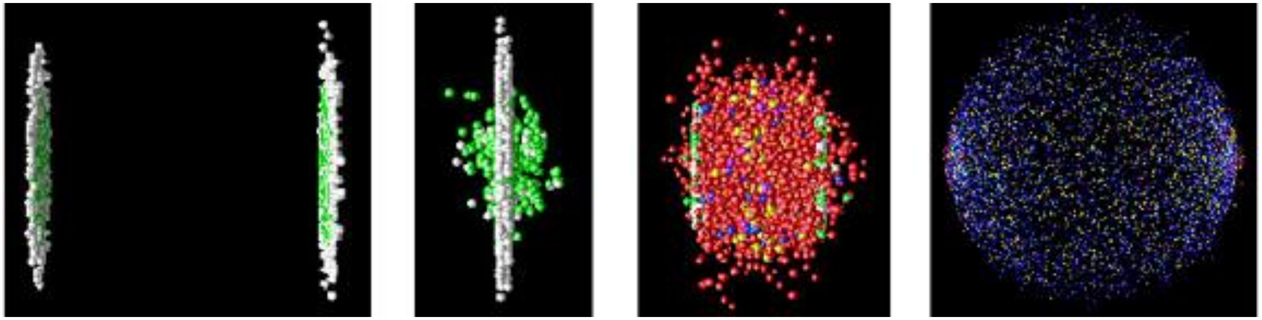
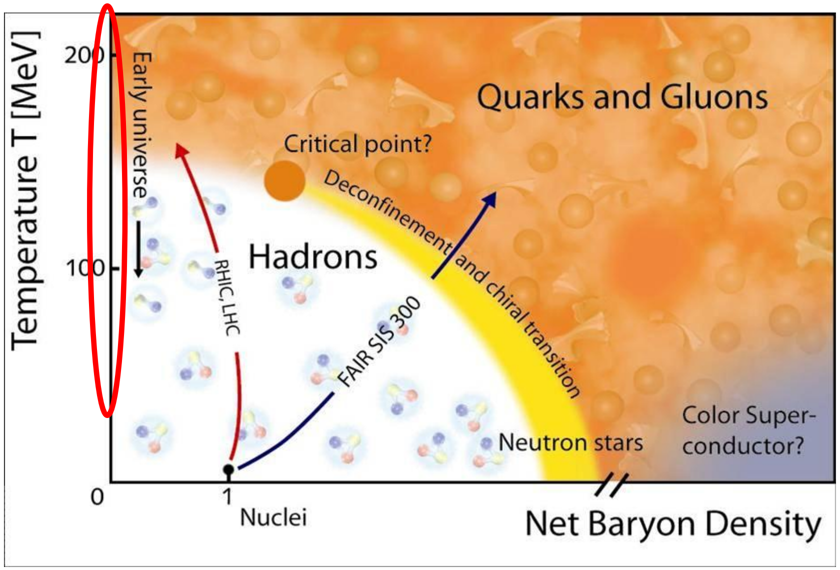
JPS meeting, Kyushu-koudai, Fukuoka, 13 Sep. 2010

Quark Gluon Plasma in Lattice QCD



from the Phenix group web-site



http://www.gsi.de/fair/experiments/

Observables in Lattice QCD

- Phase diagram in (T, μ, m_{ud}, m_s)
- Transition temperature
- Equation of state (ε/T^4, p/T^4,...)
- Hadronic excitations
- Transport coefficients
- Finite chemical potential
- etc...

Choice of quark actions on the lattice

Most (T, μ≠0) studies done with staggerd-type quarks

- less computational costs
- a part of chiral sym. preserved ...
  → N_f=2+1, almost physical quark mass, (μ≠0)

- 4th-root trick to remove unphysical "tastes"
  → non-locality "Validity is not guaranteed"

It is important to cross-check with
theoretically sound lattice quarks like Wilson-type quarks

Our aim is to investigate
QCD Thermodynamics with Wilson-type quarks

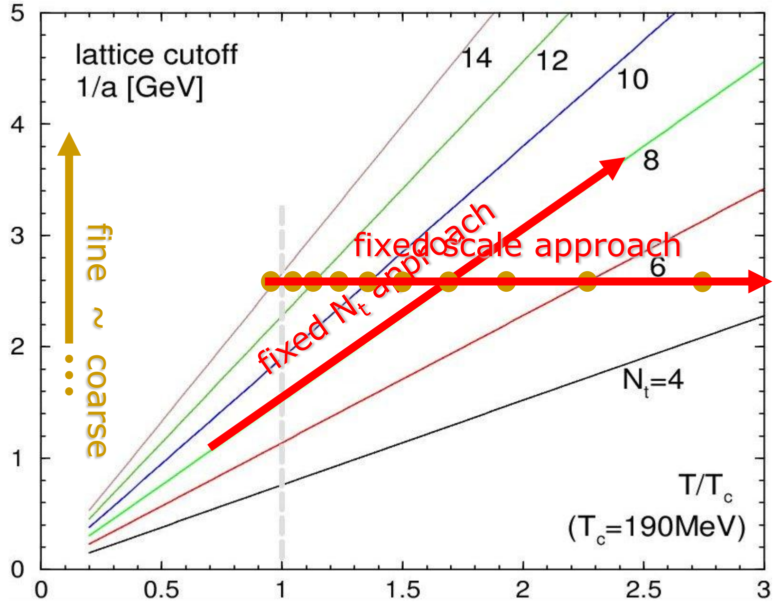
→ WHOT-QCD Collaboration

Fixed scale approach to study QCD thermodynamics

Temperature $T=1/(N_t a)$ is varied by N_t at fixed a

a : lattice spacing
N_t : lattice size in temporal direction

Temperatures in each approach

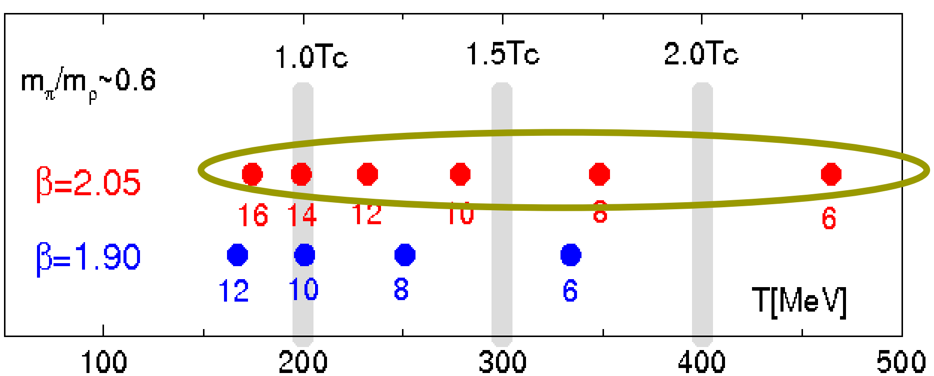


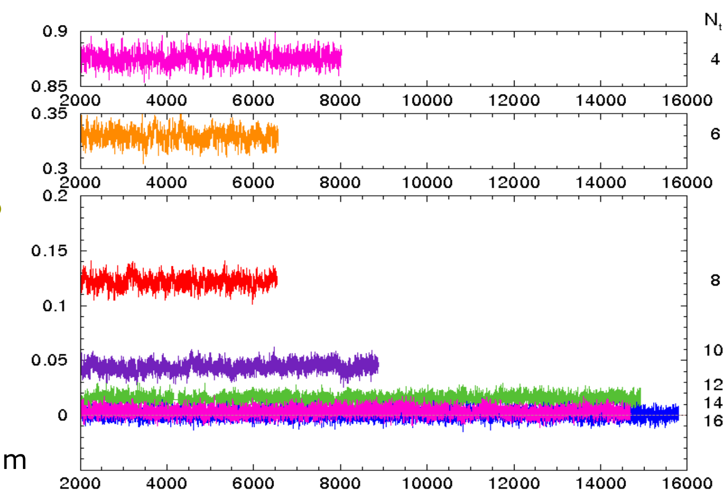
- **Advantages**
  - Line of Constant Physics
  - T=0 subtraction for renorm. (spectrum study at T=0)
  - larger 1/a in whole T region
- **Disadvantages**
  - T resolution by integer N_t
  - UV cutoff eff. at high T

T=0 & T>0 configurations for N_f=2+1 QCD

- T=0 simulation: on 28^3 x 56 by CP-PACS/JLQCD *Phys. Rev. D78 (2008) 011502*
  - RG-improved Iwasaki glue + NP-improved Wilson quarks
  - β=2.05, κ_{ud}=0.1356, κ_s=0.1351
  - V~(2 fm)^3 , a=0.07 fm, $\left(m_\pi \sim 634\text{MeV}, \ \frac{m_\pi}{m_\rho} = 0.63, \ \frac{m_{\eta_s s}}{m_\phi} = 0.74 \right)$
  - configurations available on the ILDG/JLDG
- T>0 simulations: on 32^3 x N_t (N_t=4, 6, ..., 14, 16) lattices

RHMC algorithm, same parameters as T=0 simulation





Formulation for N_f=2+1 improved Wilson quarks

$$S = S_g + S_q$$

$$S_g = -\beta \left\{ \sum_{x,\mu>\nu} c_0 W^{1\times1}_{\mu\nu}(x) + \sum_{x,\mu,\nu} c_1 W^{1\times2}_{\mu\nu}(x) \right\} \qquad \beta = \frac{6}{g^2}$$

$$S_q = \sum_{f=u,d,s} \sum_{x,y} \bar{q}^f_x D_{x,y} q^f_y$$

$$D_{x,y} = \delta_{x,y} - \kappa_f \sum_{\mu} \{(1-\gamma_\mu)U_{x,\mu}\delta_{x+\hat{\mu},y} + (1+\gamma_\mu)U^\dagger_{x-\hat{\mu},\mu}\delta_{x-\hat{\mu},y}\} - \delta_{x,y} c_{SW} \kappa_f \sum_{\mu>\nu} \sigma_{\mu\nu} F_{\mu\nu}$$

$$c_{SW}(\beta) = 1 + 0.113g^2 + 0.0209g^4 + 0.0049g^6$$

Phys. Rev. D73, 034501
CP-PACS/JLQCD

$$\frac{\epsilon - 3p}{T^4} = \frac{N_t^3}{N_s^3} \left(a\frac{\partial\beta}{\partial a} \left\langle \frac{\partial S}{\partial\beta} \right\rangle_{sub} + a\frac{\partial\kappa_{ud}}{\partial a} \left\langle \frac{\partial S}{\partial\kappa_{ud}} \right\rangle_{sub} + a\frac{\partial\kappa_s}{\partial a} \left\langle \frac{\partial S}{\partial\kappa_s} \right\rangle_{sub} \right)$$

$$\left\langle \frac{\partial S}{\partial\beta} \right\rangle = N_s^3 N_t \left(-\left\langle \sum_{x,\mu>\nu} c_0 W^{1\times1}_{\mu\nu}(x) + \sum_{x,\mu,\nu} c_1 W^{1\times2}_{\mu\nu}(x) \right\rangle + N_f \frac{\partial c_{SW}}{\partial\beta} \kappa_f \left\langle \sum_{x,\mu>\nu} \mathrm{Tr}^{(c,s)} \sigma_{\mu\nu} F_{\mu\nu} (D^{-1})_{x,x} \right\rangle \right)$$

$$\left\langle \frac{\partial S}{\partial\kappa_f} \right\rangle = N_f N_s^3 N_t \left(\left\langle \sum_{x,\mu} \mathrm{Tr}^{(c,s)} \{(1-\gamma_\mu)U_{x,\mu}(D^{-1})_{x+\hat{\mu},x} + (1+\gamma_\mu)U^\dagger_{x-\hat{\mu},\mu}(D^{-1})_{x-\hat{\mu},x}\} \right\rangle + c_{SW} \left\langle \sum_{x,\mu>\nu} \mathrm{Tr}^{(c,s)} \sigma_{\mu\nu} F_{\mu\nu} (D^{-1})_{x,x} \right\rangle \right)$$

Noise method (#noise = 1 for each color & spin indices)

Beta-functions from CP-PACS/JLQCD results

Trace anomaly needs Beta-functions in N_f=2+1 QCD

$$\frac{\epsilon - 3p}{T^4} = \frac{N_t^3}{N_s^3}\left(a\frac{\partial \beta}{\partial a}\left\langle \frac{\partial S}{\partial \beta} \right\rangle_{sub} + a\frac{\partial \kappa_{ud}}{\partial a}\left\langle \frac{\partial S}{\partial \kappa_{ud}} \right\rangle_{sub} + a\frac{\partial \kappa_{s}}{\partial a}\left\langle \frac{\partial S}{\partial \kappa_{s}} \right\rangle_{sub} \right)$$

Direct fit method Phys. Rev. D64 (2001) 074510

fit $\beta, \kappa_{ud}, \kappa_s$ as functions of $(am_\rho), \left(\frac{m_\pi}{m_\rho}\right), \left(\frac{m_{\eta_{ss}}}{m_\phi}\right)$

$$\begin{pmatrix} \beta \\ \kappa_L \\ \kappa_S \end{pmatrix} = \vec{c}_1 + \vec{c}_2(am_\rho) + \vec{c}_3(am_\rho)^2 + \vec{c}_4\left(\frac{m_\pi}{m_\rho}\right) + \vec{c}_5\left(\frac{m_\pi}{m_\rho}\right)^2 + \vec{c}_6(am_\rho)\left(\frac{m_\pi}{m_\rho}\right)$$
$$+ \vec{c}_7\left(\frac{m_{\eta_{ss}}}{m_\phi}\right) + \vec{c}_8\left(\frac{m_{\eta_{ss}}}{m_\phi}\right)^2 + \vec{c}_9(am_\rho)\left(\frac{m_{\eta_{ss}}}{m_\phi}\right) + \vec{c}_{10}\left(\frac{m_\pi}{m_\rho}\right)\left(\frac{m_{\eta_{ss}}}{m_\phi}\right)$$

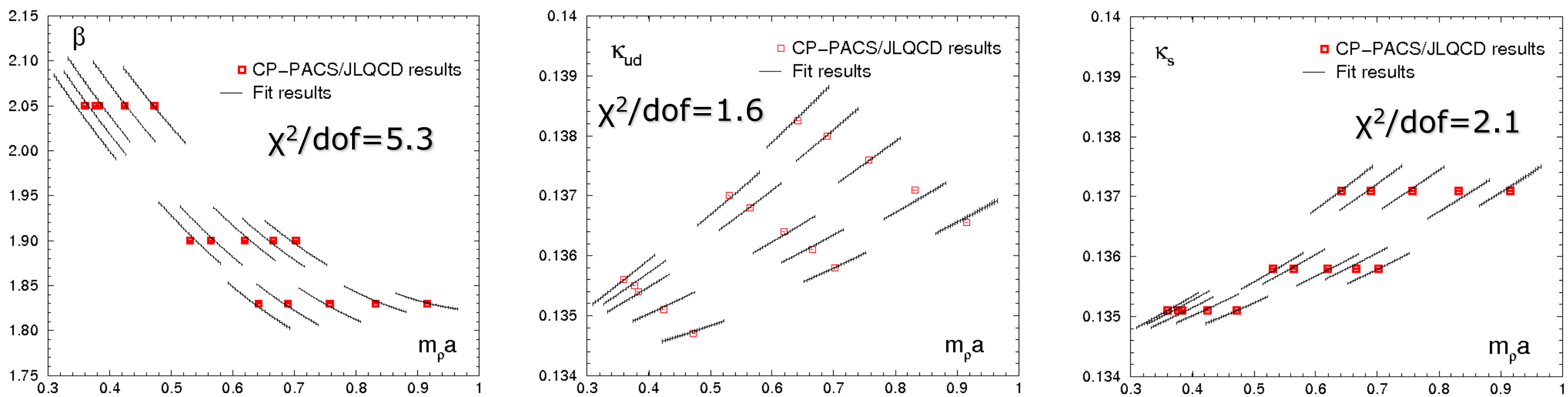
$am_\rho \frac{\partial X}{\partial (am_\rho)}$ with fixed $\left(\frac{m_\pi}{m_\rho}\right), \left(\frac{m_{\eta_{ss}}}{m_\phi}\right)$ $(X = \beta, \kappa_{ud}, \kappa_s)$

Beta-functions from CP-PACS/JLQCD results

Meson spectrum by CP-PACS/JLQCD *Phys. Rev. D78 (2008) 011502.*

3 (β) x 5 (κ_{ud}) x 2 (κ_s) = 30 data points

fit β,κ_{ud},κ_s as functions of $(am_\rho), \left(\frac{m_\pi}{m_\rho}\right), \left(\frac{m_{\eta_{ss}}}{m_\phi}\right)$



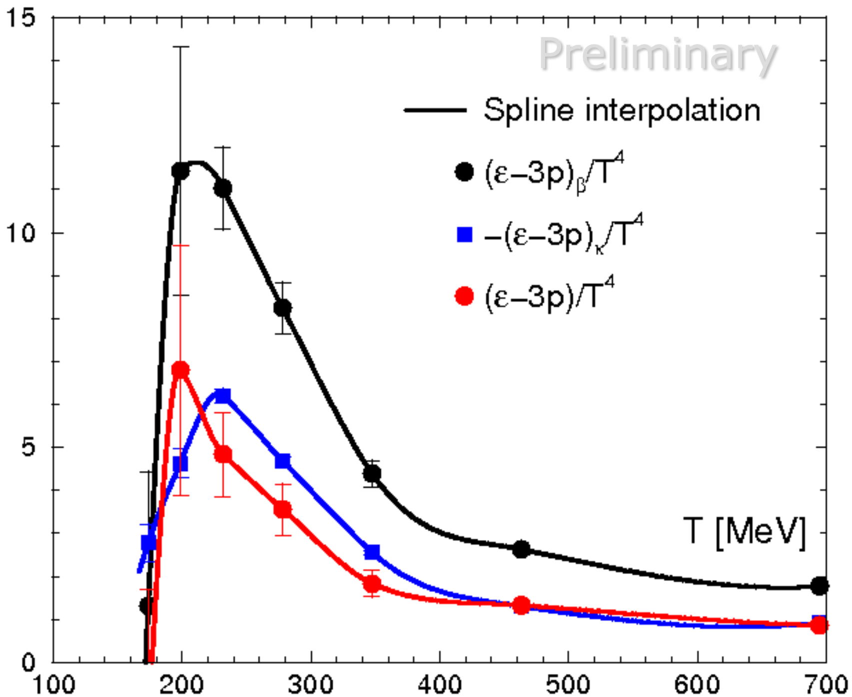
$$\left(a\frac{\partial\beta}{\partial a},\ a\frac{\partial\kappa_{ud}}{\partial a},\ a\frac{\partial\kappa_s}{\partial a} \right)_{\text{simulation point}}$$

$$= (-0.334(4),\ 0.00289(6),\ 0.00203(5))$$

only statistical error

Trace anomaly in N_f=2+1 QCD

$$\frac{\epsilon - 3p}{T^4} = \frac{N_t^3}{N_s^3}\left(\underbrace{a\frac{\partial \beta}{\partial a}\left\langle \frac{\partial S}{\partial \beta}\right\rangle_{sub}}_{(\epsilon-3p)_\beta/T^4} + \underbrace{a\frac{\partial \kappa_{ud}}{\partial a}\left\langle \frac{\partial S}{\partial \kappa_{ud}}\right\rangle_{sub} + a\frac{\partial \kappa_s}{\partial a}\left\langle \frac{\partial S}{\partial \kappa_s}\right\rangle_{sub}}_{(\epsilon-3p)_\kappa/T^4}\right) \qquad S = S_g + S_q$$



Nt	config. (x 5MD traj.) S_g	S_q (**)
56	1300(*)	980
16	1542	647
14	1448	647
12	1492	695
10	863	487
8	628	520
6	657	360
4	802	295

(*) T=0 (Nt=56) by CP-PACS/JLQCD
S_g calculated with 6500traj.
(**) thermal. = 1000 traj.

Trace anomaly in N_f=2+1 QCD

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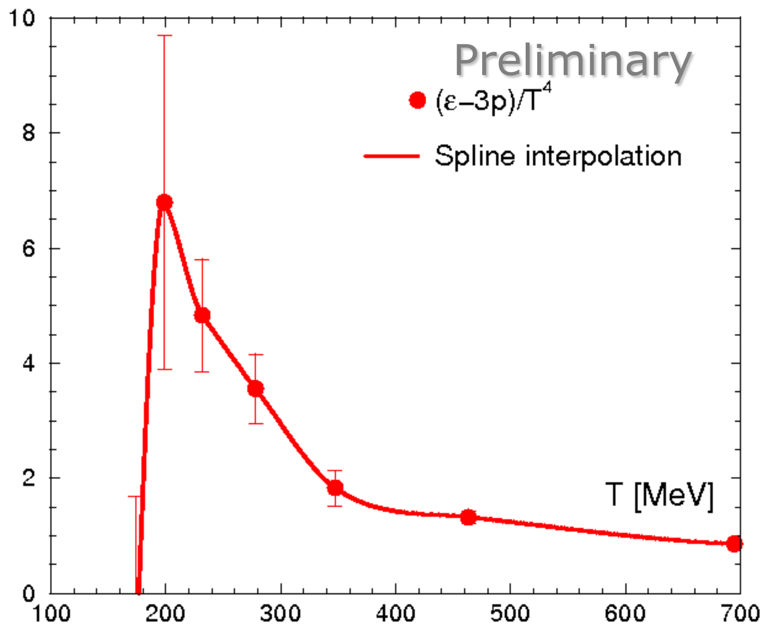
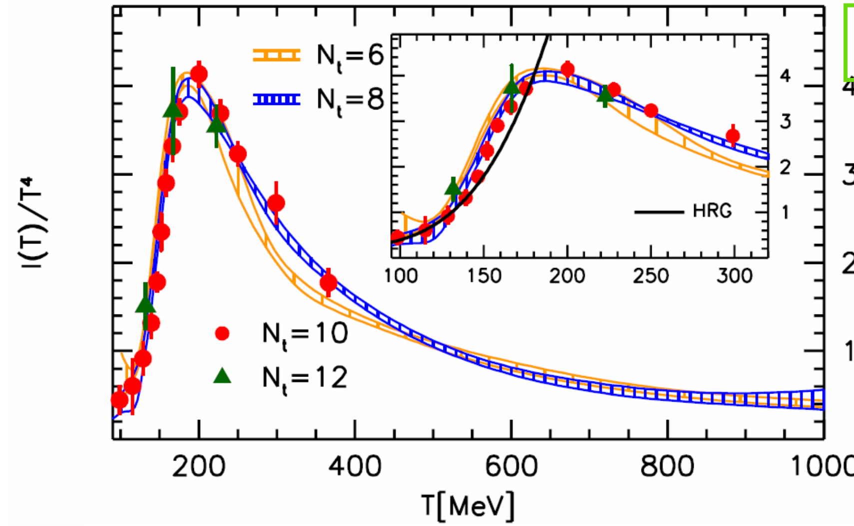
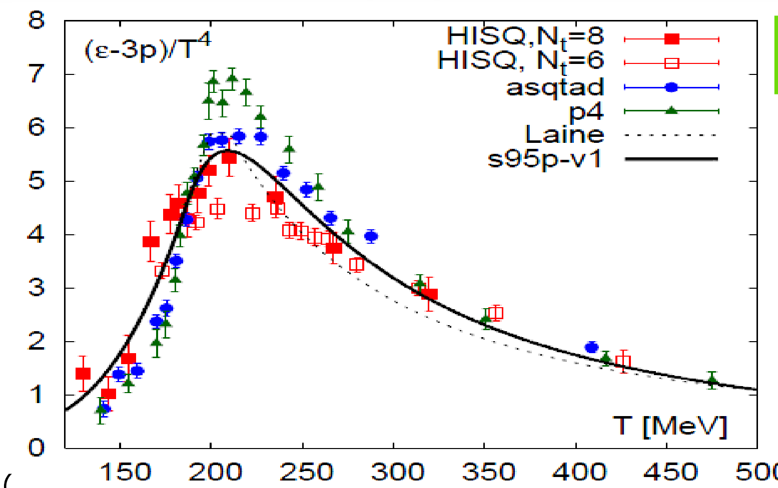


stout



S. Borsanyi et al., arXiv:1007.2580

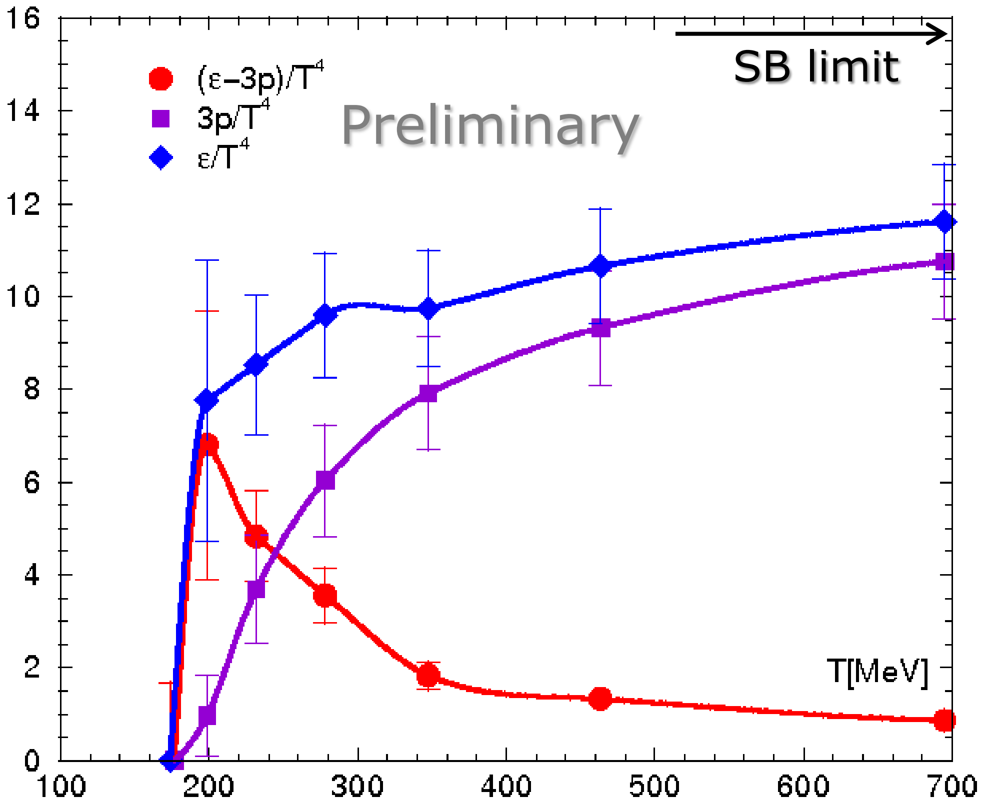
HISQ



HotQCD, arXiv:1005.1131

- peak height = 4~6
  in recent Staggered results
  ($m_q \sim m_q^{phys.}$)

Equation of State in Nf=2+1 QCD



- T-integration

$$\frac{p}{T^4} = \int_0^T dT' \frac{\epsilon - 3p}{T'^5}$$

is performed by the trapezoidal rule (straight line interpolation).

- ε/T^4 is calculated from

$$\frac{\epsilon - 3p}{T^4} + \frac{3p}{T^4}$$

- Large error in whole T region

Summary & outlook

We presented the EOS in N_f=2+1 QCD using improve Wilson quarks

- Equation of state

  More statistics are needed in the lower temperature region

  Results at different scales (β=1.90 by CP-PACS/JLQCD)

- N_f=2+1 QCD just at the physical point

  the physical point (pion mass ~ 140MeV) by PACS-CS

  β=1.90 is appropriate to control stat. error at lower T.

  Odd Nt config. generation is necessary.

- Finite density

  Taylor expansion method to explore EOS at $\mu \neq 0$

T-integration method to calculate the EOS

We propose a new method ("T-integration method")
to calculate the EOS at fixed scales

T.Umeda et al. (WHOT-QCD), Phys.Rev.D79 (2009) 051501(R)

Our method is based on the trace anomaly (interaction measure),

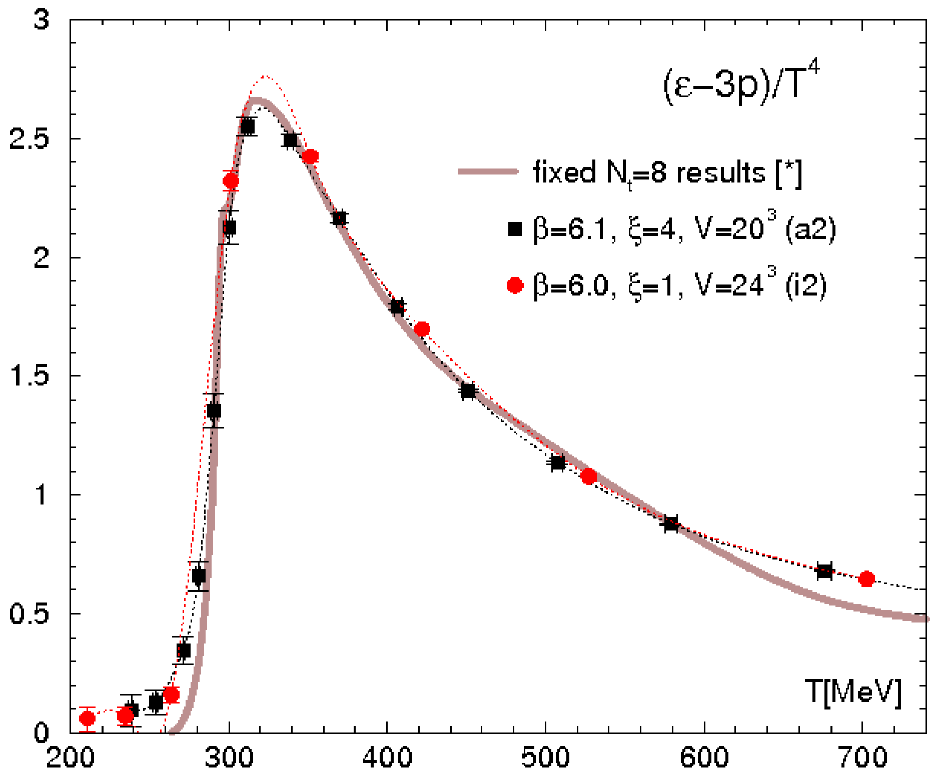
$$\frac{\epsilon - 3p}{T^4} = \left(\frac{N_t^3}{N_s^3}\right) a \frac{d\beta}{da} \left\langle \frac{dS}{d\beta} \right\rangle_{sub}$$

and the thermodynamic relation.

$$\frac{\epsilon - 3p}{T^4} = T \frac{\partial (p/T^4)}{\partial T}$$

$$\Longrightarrow \quad \frac{p}{T^4} = \int_0^T dT' \, \frac{\epsilon - 3p}{T'^5}$$

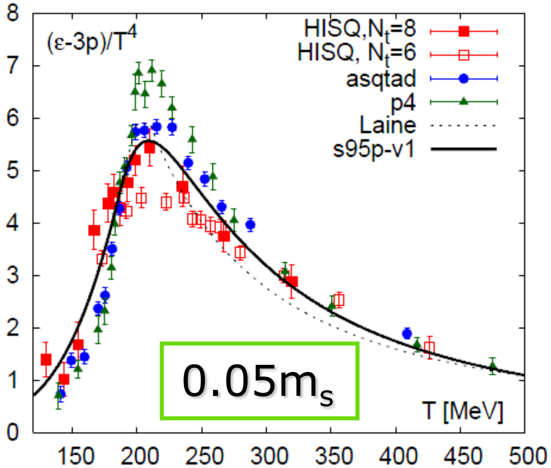
Test in quenched QCD

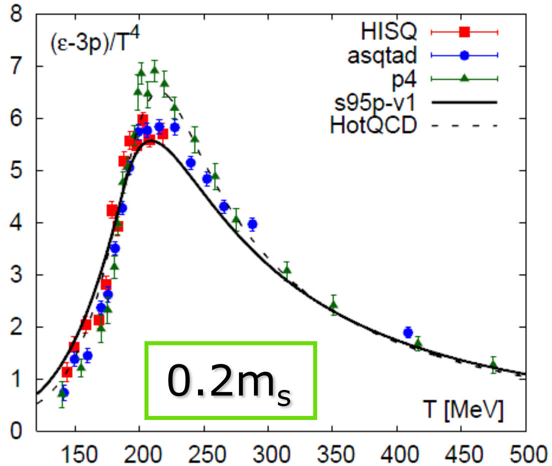


[*] G. Boyd et al., NPB469, 419 (1996)

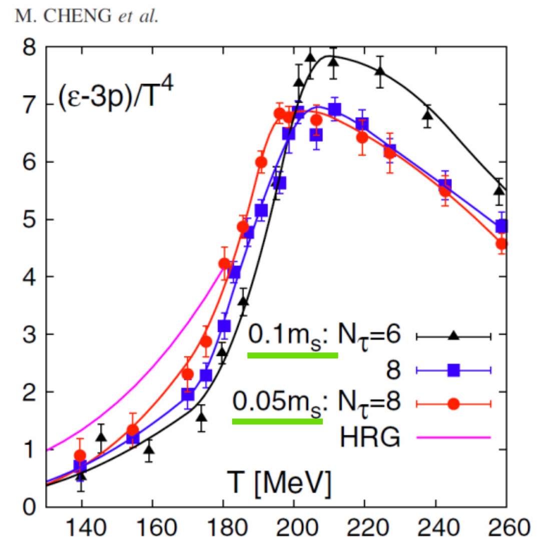
- Our results are roughly consistent with previous results.
- Our results deviate from the fixed N_t=8 results [*] at higher T (aT~0.3 or higher)
- Trace anomaly is sensitive to spatial volume at lower T (below T_c). V > $(2\text{fm})^3$ is ncessarry.

Quark mass dependence of Trace anomaly

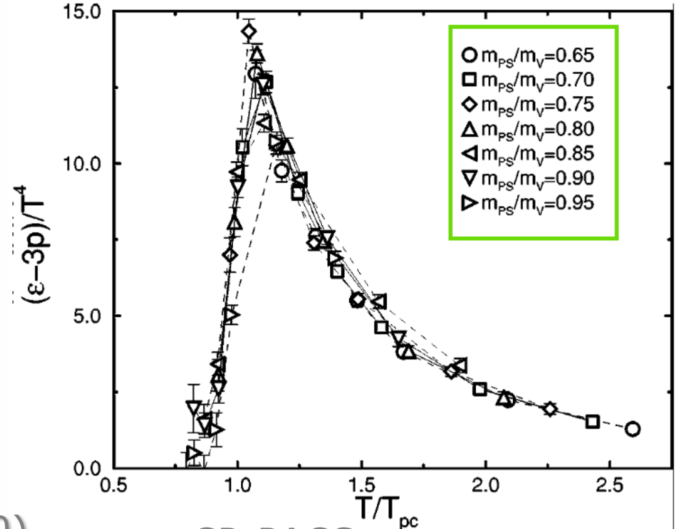




HotQCD arXiv1005.1131



HotQCD PRD91,054504(2010)



CP-PACS PRD64,074510 (2001)

- peak height of the Trace anomaly
  → small quark mass dependence
- Our result seems to be reasonable !
  but small m_q is necessary.