ウィルソンフェルミオンを用いた有限温度格子ＱＣＤの研究

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This talk is (partly) based on *Phys.Rev.D79 (2009) 051501(R).*

T.U, S. Ejiri, S. Aoki, T. Hatsuda, K. Kanaya, Y. Maezawa, and H. Ohno
(WHOT-QCD Collaboration)

HadNucl09, KEK, Ibaraki, Japan, 13 Aug. 2009

Contents of this talk

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

- Brief review on Lattice QCD at finite T (zero μ)
- Why do we need "Hot QCD with Wilson-type quarks" ?
- Why is "Hot QCD with Wilson-type quarks" difficult ?
- How do we overcome the difficulties ?
  - We propose "T-integration method"
  - Test in quenched QCD
- Toward Nf=2+1 QCD Thermodynamics

Introduction

Physics in Lattice QCD at finite temperature

- Phase diagram in (T, μ , m_{ud}, m_s)
- Transition temperature
- Equation of state (e, p, s,...)

} quantitative studies

- Heavy quarkonium
- Transport coefficients (shear/bulk viscosity)
- Finite chemical potential

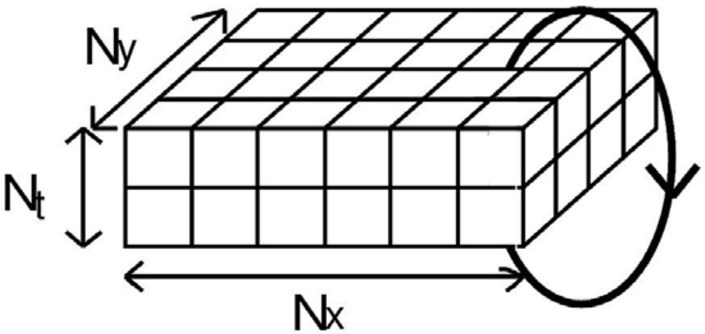
} qualitative studies

- etc...

These are important to study

- Quark Gluon Plasma in Heavy Ion Collision exp.
- Early universe
- Neutron star
- etc...

Hot QCD on the lattice



Finite T Field Theory on the lattice

- 4dim. Euclidean lattice
- gauge field $U_\mu(x)$ → periodic B.C.
- quark field $q(x)$ → anti-periodic B.C.
- Temperature $T=1/(N_t a)$

Input parameters :	β $(=6/g^2)$	(lattice gauge coupling)
(Nf=2+1 QCD)	am_{ud}	(light (up & down) quark masses)
	am_s	(strange quark mass)
	N_t	(temperature)

(*) lattice spacing "a" is not an input parameter

$a=a(\beta, am_{ud}, am_s)$

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

Fermions on the lattice

Lattice QCD

Path integral is carried out by Monte Carlo Integration

QCD action is defined on the lattice

Fermion doubling problem

- naive discretization causes 2^4 doublers
- Nielsen-Ninomiya's No-go theorem

  → Doublers appear unless chiral symmetry is broken

- KS (Staggered) fermion
  - 16 doublers = 4 spinors x 4 flavors ("tastes")
  - Remnant U(1) symmetry
  - Fourth root trick : still debated
  - Numerical cost is low

and …

Fermions on the lattice

- Wilson fermion
  - adds the Wilson term to kill extra 2^4-1 doublers
  - breaks chiral symmetry explicitly → additive mass renorm.
  - Improved version (Clover fermion) is widely used.
  - Numerical cost is moderate

- Domain Wall fermion
  - 5dim. formulation
  - Symmetry breaking effect $m_{res} \to 0$ as $N_5 \to \infty$
  - Numerical cost is high

- Overlap fermion
  - Exact chiral symmetry
  - Numerical cost is very high

Recent lattice calculations of EOS

Hot-QCD: aT=1/4, 1/6, 1/8 KS (p4 & Asqtad) quark $T=1/(aN_t)$
pion mass ~ 220MeV, $N_f=2+1$
arXiv:0903.4379 [het-lat]
p4 (RBC-Bielefeld Collab.)
Asqtad (MILC Collab.)

Wuppertal: aT=1/4, 1/6 KS (stout) quark
pion mass ~ 140MeV, $N_f=2+1$
JHEP 0601 (2006) 089

CP-PACS: aT=1/4, 1/6 Wilson (MFI Clover) quark
pion mass ~ 500MeV, $N_f=2$
Phys. Rev. D64 (2001) 074510

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Problems in QCD Thermo. with KS fermions

Many QCD thermo. calc. were done with KS fermions.

- Phase diagram

  $N_f=2$ massless QCD → O(4) critical exponets
  KS fermion does not exhibit expected O(4) scaling
  C. Bonati et al. (KS $N_f=2$) → (1st order ?)
  (Wilson fermion shows O(4), but at rather heavy masses)

  RBC-Bi & Wuppertal (KS $N_f=2+1$) → crossover

Transition temperature (crossover transition in KS studies)

KS results are not consistent with each other

MILC :	169(12)(4)MeV(*)	*Phys. Rev. D71 (2005) 034504*
RBC-Bi :	192(7)(4)MeV	*Phys. Rev. D74 (2006) 054507*
Wuppertal :	146(2)(3)MeV	*JHEP06 (2009) 088*

(*)T_c at $m_q=0$

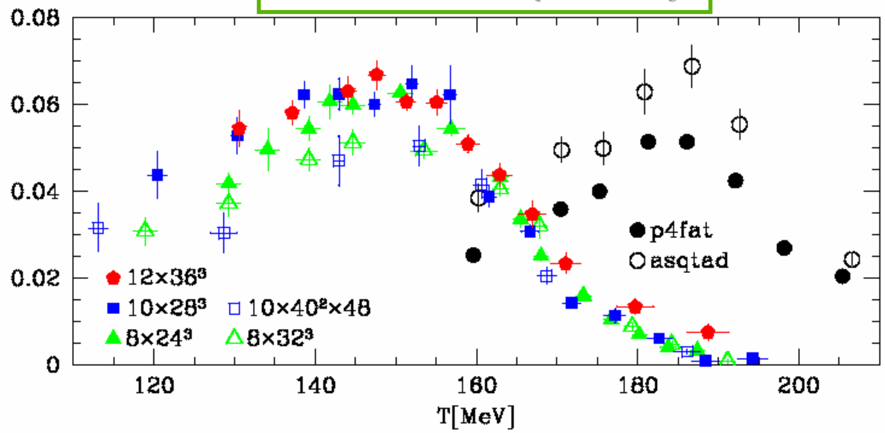
Wuppertal → $T_c(L) \neq T_c(\chi)$, Hot-QCD → $T_c(L)=T_c(\chi)$,

- EOS

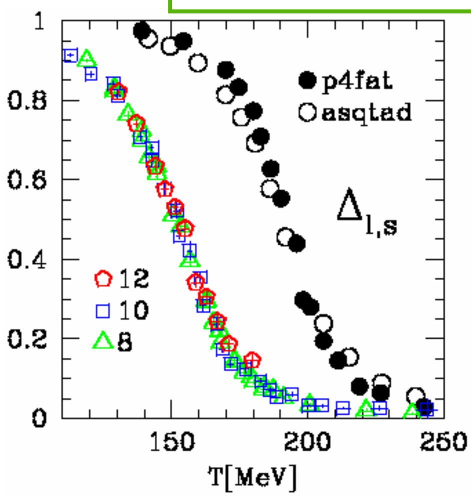
  KS results are not consistent with each other

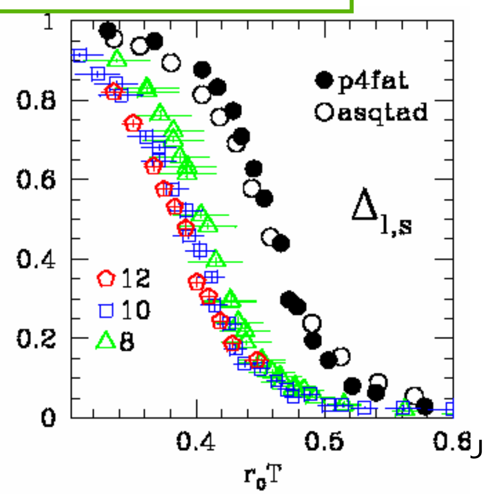
Hot-QCD Collab. vs Wuppertal group

chiral susceptibility



renormalized chiral condensate





Y.Aoki et al., JHEP06 (2009) 088

(In Sect.4: conclusions, outlooks)
As a final remark we have to mention that the staggered formalism used in this work and all other large scale thermodynamics studies may suffer from theoretical problems. To date it is not proven that the staggered formalism with 2+1 flavors really describes QCD in the continuum limit. Therefore it is desirable to also study QCD thermodynamics with a theoretically firmly established (e.g. Wilson type) fermion discretization.

We have to study the QCD-EOS with Wilson-type fermions !!

Univ.)

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Integral method to calculate pressure p/T^4

$p = \frac{T}{V} \ln Z$ for large volume system

Lattice QCD can not directly calculate the partition function $\ln Z$

however its derivative is possible $\frac{\partial}{\partial \beta} \ln Z = -\left\langle \frac{\partial S_{QCD}}{\partial \beta} \right\rangle$

One can obtain p as the integral of derivative of p

high temp.

low temp. with p≃0

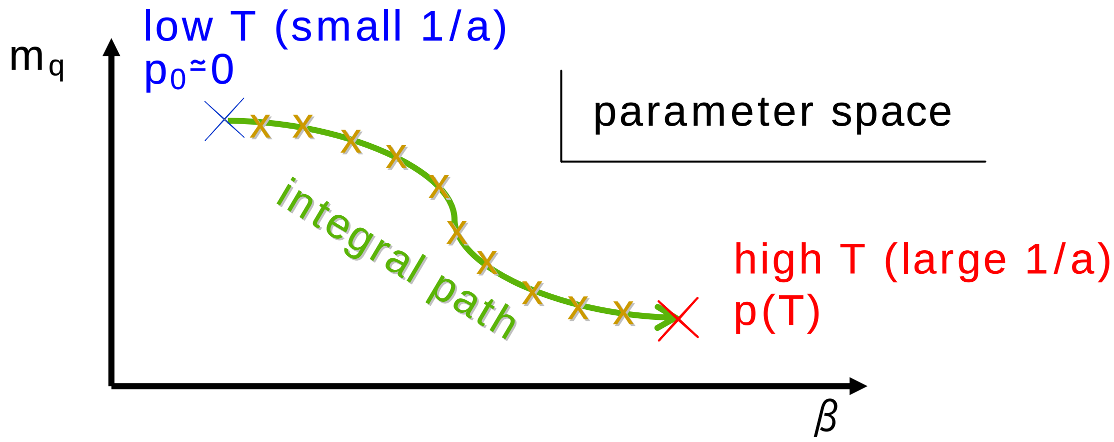
$$\left.\frac{p}{T^4}\right|_{\beta_0}^{\beta} = \frac{1}{VT^3}\int_{\beta_0}^{\beta} d\beta' \frac{\partial}{\partial \beta'} \ln Z$$

$$= -N_t^4 \int_{\beta_0}^{\beta} d\beta' \frac{1}{N_s^3 N_t} \left(\langle \frac{\partial S_{QCD}}{\partial \beta} \rangle_{T>0} - \langle \frac{\partial S_{QCD}}{\partial \beta} \rangle_{T=0} \right)$$

T=0 subtraction

Line of constant physics (LCP)

In case of $N_f=2+1$ QCD
there are three (bare) parameters: β, (am_{ud}) and (am_s)



- The physics (observables) should be kept along the integral path.
  ➔ Line of Constant Physics (LCP) defined at T=0
  Inaccuracy of the LCP is a source of systematic error in EOS.
- Integral on the path is carried out numerically.
  T=0 subtractions are necessary at each point.

Numerical cost for EOS calculations

In the EOS calculation,

T=0 calculations dominate in spite of T>0 study.

- Search for a Line of Constant Physics (LCP)
- T=0 subtraction at each temperature

T=0 simulations are time consuming.

- N_t is sufficiently large (e.g. 24^3x24 at T=0, 24^3x6 at T>0)
- small Dirac eigenvalues (larger cost for $D^{-1}(x,y)$)

(cost at T=0) = (5~20) x (cost at T>0)

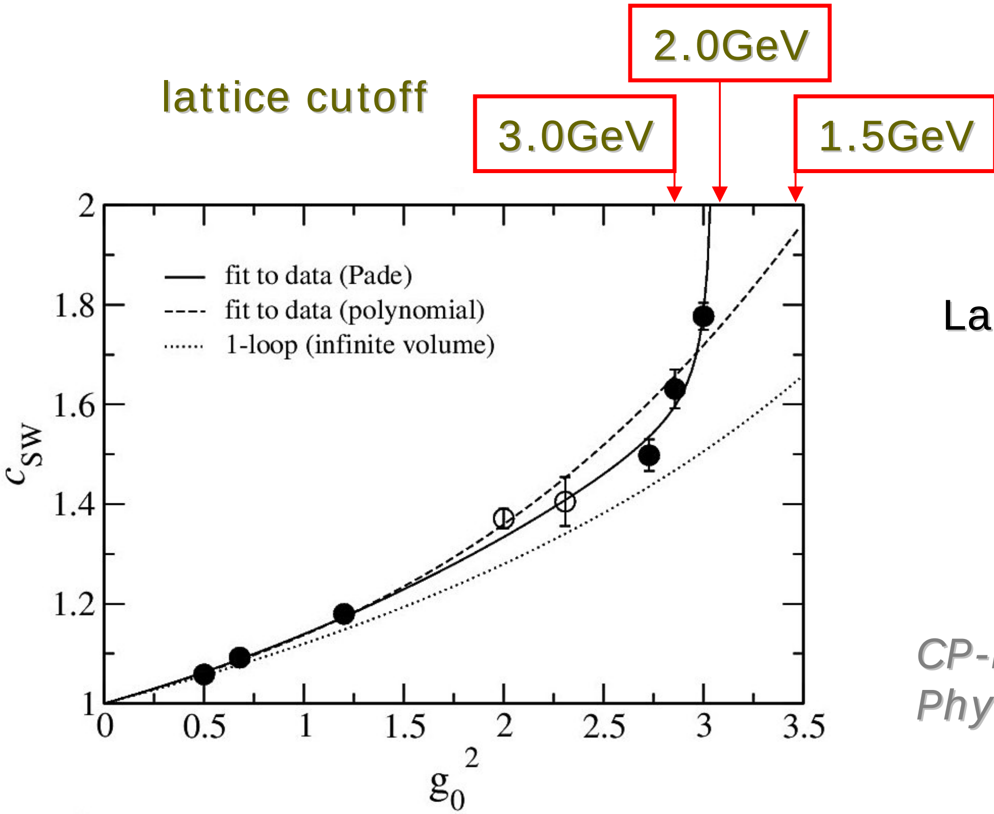
Even with the KS fermions,

EOS at N_t=8 is the best with current computer resources.

Further problems in Wilson-type quarks

Nonperturbative improvement of Wilson fermions :
clover coefficient c_{sw} by the Schrodinger functional method

lattice cutoff

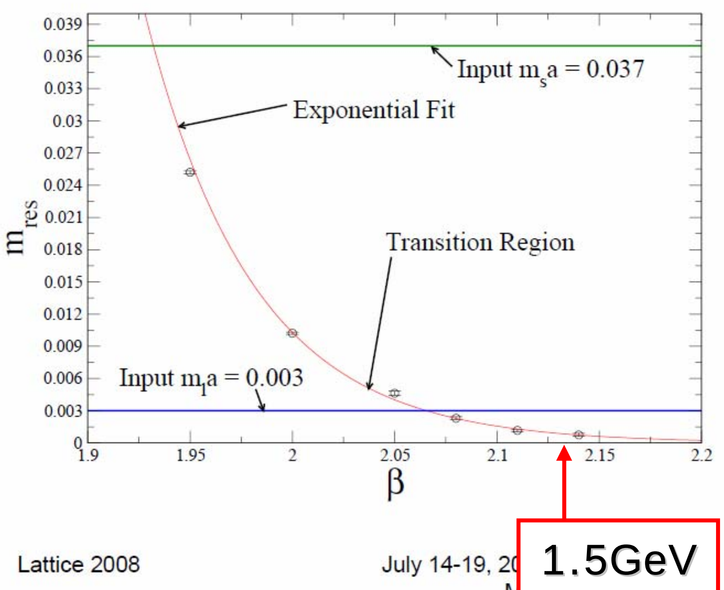


Large uncertainty of c_{sw}
at 1/a < 2GeV

CP-PACS,
Phys. Rev. D73 (2006) 034501

Further problems in Wilson-type quarks

Residual quark mass m_{res} in Domain Wall fermion



- **m_{res}** increases exponentially with decreasing β for L_s=32
- Total quark mass is not fixed with β → increases as we go to coarser lattices
- **m_{res}** dominated by non-perturbative lattice dislocations, suppressed by only $1/L_s$

Lattice 2008 July 14-19, 20 Mary 7

Residual quark mass is not well controlled at 1/a < 2GeV (at typical L_s)

RBC & Hot-QCD, Lattice 2008

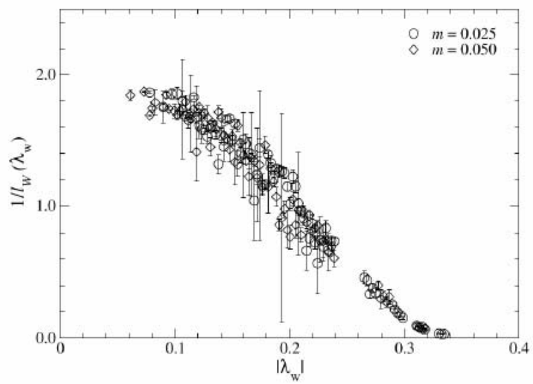
RBC & HOT-QCD Collab. gave up N_t=8, L_s=32 Domain Wall project.
→ N_t=8, L_s=96 project on progress

Further problems in Wilson-type quarks

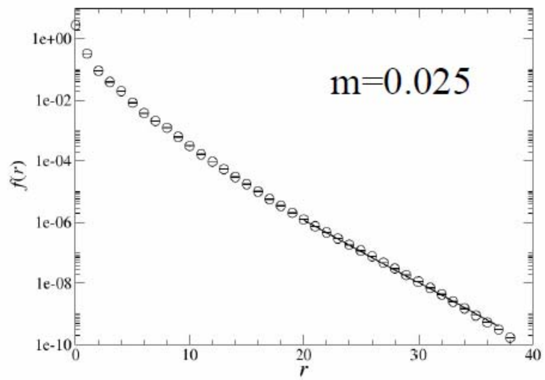
Locality

JLQCD, 2008; JLQCD (Yamada et al.), Proc. of Lattice 2006

- At beta=2.3 (Nf=2) overlap fermion



Localization length of low eigenmodes of H_W



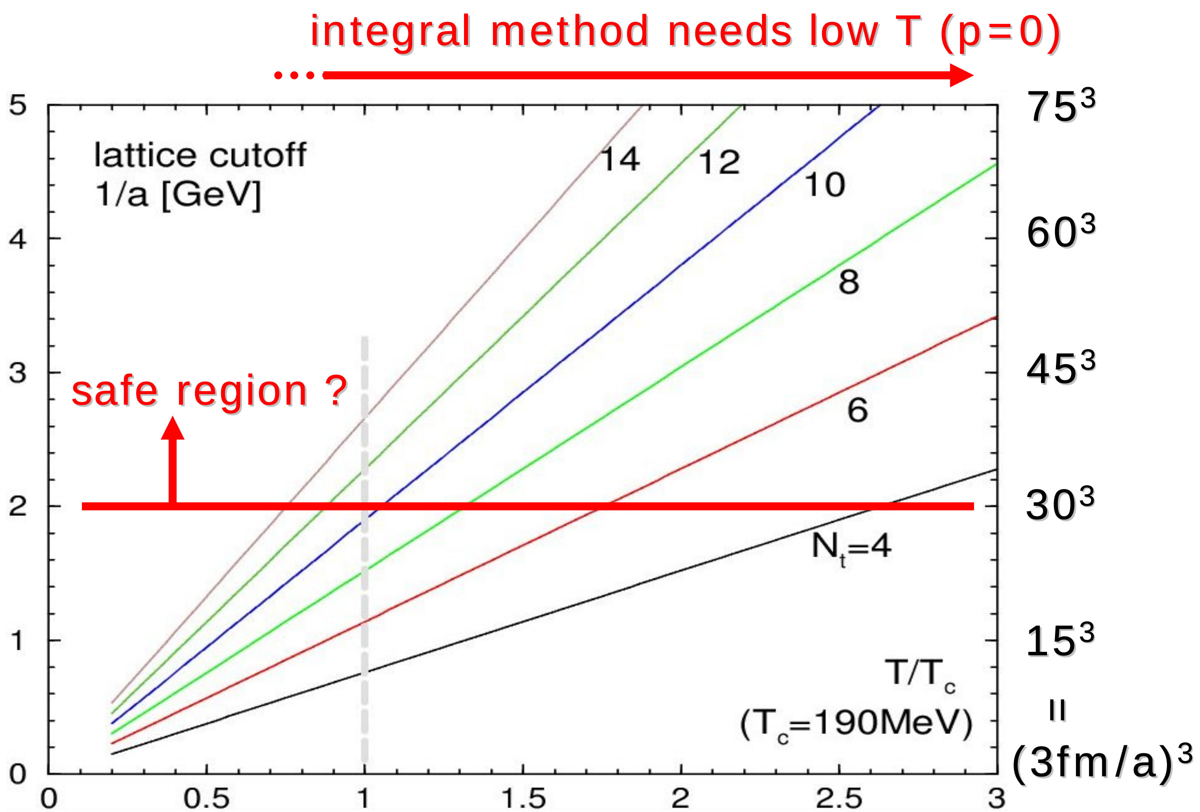
Localization of overlap operator
$l = 0.25\text{fm}$ (~$2a$)

JLQCD, TQFT(YITP) 2008

Coarse lattice generally causes various problems.
→ 1/a > 2GeV is safe to calculate physics at T=0 & T>0.

How large Nt is safe ?

T vs 1/a at various Nt



- Situation for T_c calc. is similar to the EOS
- Phase diagram study needs more cost !!

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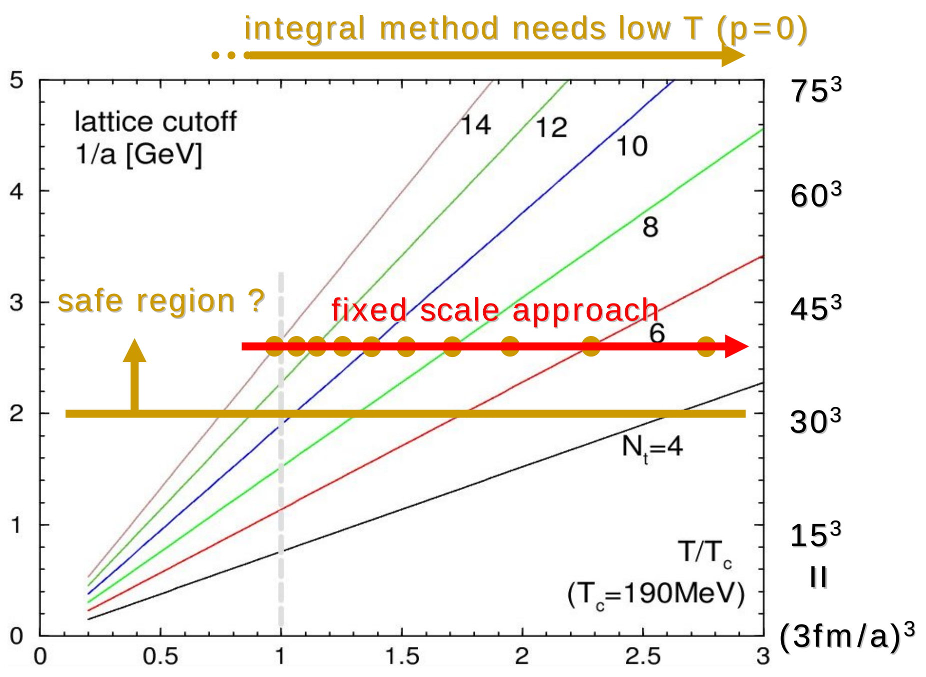
Fixed scale approach to study QCD thermodynamics

Temperature $T=1/(N_t a)$ is varied by N_t at fixed $a(\beta, m_{ud}, m_s)$



- **Advantages**
  - LCP is trivially exact
  - T=0 subtraction is done with a common T=0 sim. (T=0 high. stat. spectrum)
  - easy to keep large 1/a at whole T region
  - easy to study T effect without V, 1/a effects
- **Disadvantages**
  - T resolution by integer N_t
  - program for odd N_t
  - 1/a = const. is not suited for high T limit study

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.

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

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

Simulation parameters (isotropic lattices)

We present results from SU(3) gauge theory as a test of our method

- plaquette gauge action on N_s^3 x N_t lattices
- Jackknife analysis with appropriate bin-size

To study scale- & volume-dependence,
we prepare 3-type of lattices.

(1) β =6.0, V=(16a)^3
1/a=2.1GeV

β	N_s	N_t	T[MeV]	conf.
6.0	16	16	~ 0	350k
6.0	16	10	210	350k
6.0	16	9	230	250k
6.0	16	8	260	200k
6.0	16	7	300	100k
6.0	16	6	350	50k
6.0	16	5	420	50k
6.0	16	4	530	50k
6.0	16	3	700	50k

(2) β =6.0, V=(24a)^3
1/a=2.1GeV

β	N_s	N_t	T[MeV]	conf.
6.0	24	16	~ 0	150k
6.0	24	10	210	250k
6.0	24	9	230	200k
6.0	24	8	260	150k
6.0	24	7	300	100k
6.0	24	6	350	50k
6.0	24	5	420	50k
6.0	24	4	530	50k
6.0	24	3	700	50k

(3) β =6.2, V=(22a)^3
1/a=2.5GeV

β	N_s	N_t	T[MeV]	conf.
6.2	22	22	~ 0	250k
6.2	22	13	220	350k
6.2	22	12	240	350k
6.2	22	11	270	350k
6.2	22	10	290	250k
6.2	22	9	320	200k
6.2	22	8	360	200k
6.2	22	7	420	100k
6.2	22	6	490	100k
6.2	22	5	580	50k
6.2	22	4	730	50k

Simulation parameters (anisotropic lattice)

Anisotropic lattice is useful to increase Temp. resolution,
we also test our method on an anisotropic lattice $a_s \neq a_t$

- plaquette gauge action on N_s^3 x N_t lattices
  with anisotropy $\xi = a_s/a_t = 4$

β	N_s	N_t	T[MeV]	conf.
6.1	20	80	~ 0	220k
6.1	20	32	250	520k
6.1	20	30	270	220k
6.1	20	29	280	220k
6.1	20	28	290	220k
6.1	20	27	300	220k
6.1	20	26	310	220k
6.1	20	24	340	220k
6.1	20	22	370	220k
6.1	20	20	410	220k
6.1	20	18	450	220k
6.1	20	16	510	220k
6.1	20	14	580	220k
6.1	20	12	680	220k
6.1	20	10	810	220k
6.1	20	8	1010	220k

$\beta = 6.1$, $\xi = 4$
$V = (20a_s)^3$
$= (1.95\text{fm})^3$
$1/a_s = 2.0\text{GeV}$
$1/a_t = 8.1\text{GeV}$

- EOS calculation
- static quark free energy

β	N_s	N_t	T[MeV]	conf.
6.1	20	30	270	220k
6.1	20	29	280	220k
6.1	20	28	290	220k
6.1	20	27	300	220k
6.1	20	26	310	220k
6.1	30	30	270	80k
6.1	30	29	280	100k
6.1	30	28	290	180k
6.1	30	27	300	100k
6.1	30	26	310	80k
6.1	40	30	270	70k
6.1	40	29	280	130k
6.1	40	28	290	300k
6.1	40	27	300	140k
6.1	40	26	310	70k

$V = (20a_s)^3$
$= (1.95\text{fm})^3$

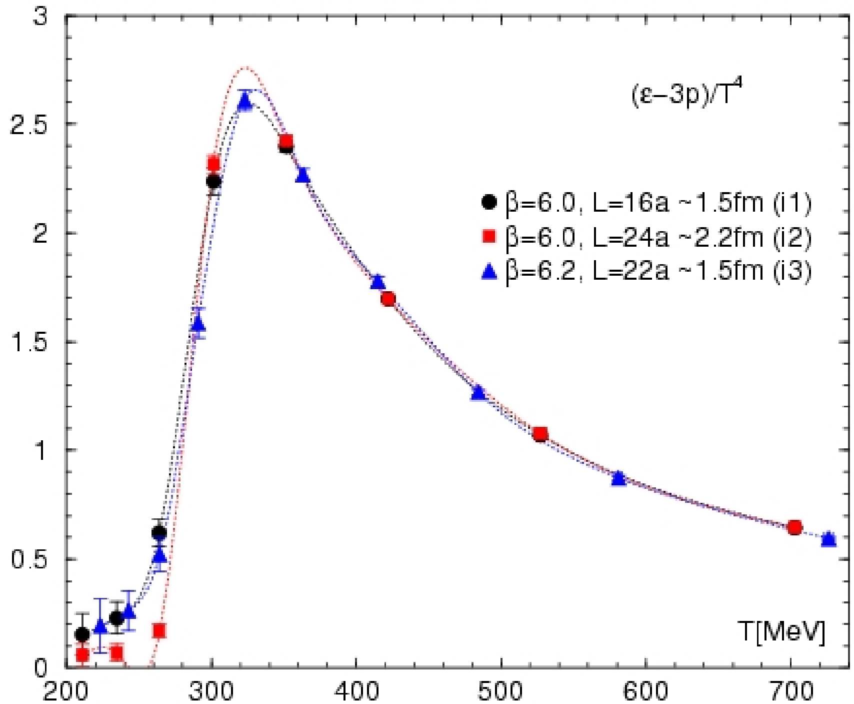
$V = (30a_s)^3$
$= (2.92\text{fm})^3$

$V = (40a_s)^3$
$= (3.89\text{fm})^3$

- critical temp.

Trace anomaly $(e - 3p)/T^4$ on isotropic lattices

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



dotted lines : cubic spline

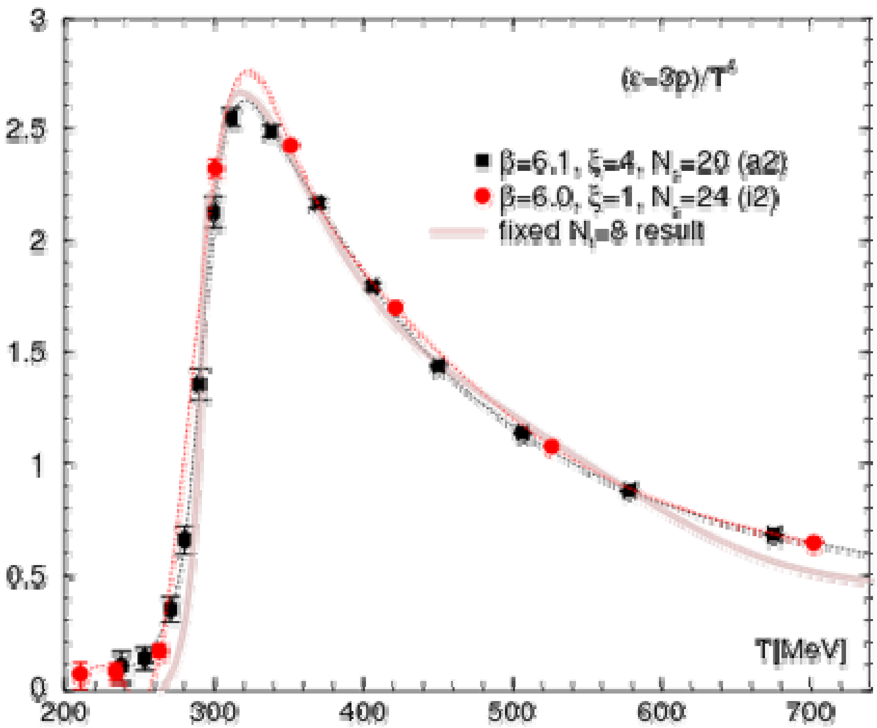
(1) β =6.0, 1/a=2.1GeV, V=(1.5fm)^3
(2) β =6.0, 1/a=2.1GeV, V=(2.2fm)^3
(3) β =6.2, 1/a=2.5GeV, V=(1.5fm)^3

beta function : G.Boyd et al. ('96)
lattice scale r_0 : R.Edwards et al. ('98)

- Good agreement between (1) and (3)
  → scale violation is small
  1/a=2GeV is good
- Finite volume effect appears below & near T_c
  → volume size is important
  V=(2fm)^3 is necessary.

Trace anomaly (e - 3p)/T^4 on aniso. lattice

$$\frac{\epsilon - 3p}{T^4} = \left(\frac{N_t^3}{N_s^3 \xi^3}\right) a_s \frac{\partial \beta}{\partial a_s}\Big|_\xi \left\langle \frac{\partial S_g}{\partial \beta}\Big|_\xi \right\rangle$$



dotted lines : cubic spline

(1) ξ =4, 1/a_s=2.0GeV, V=(2.0fm)^3

(2) ξ =1, 1/a=2.1GeV, V=(2.2fm)^3

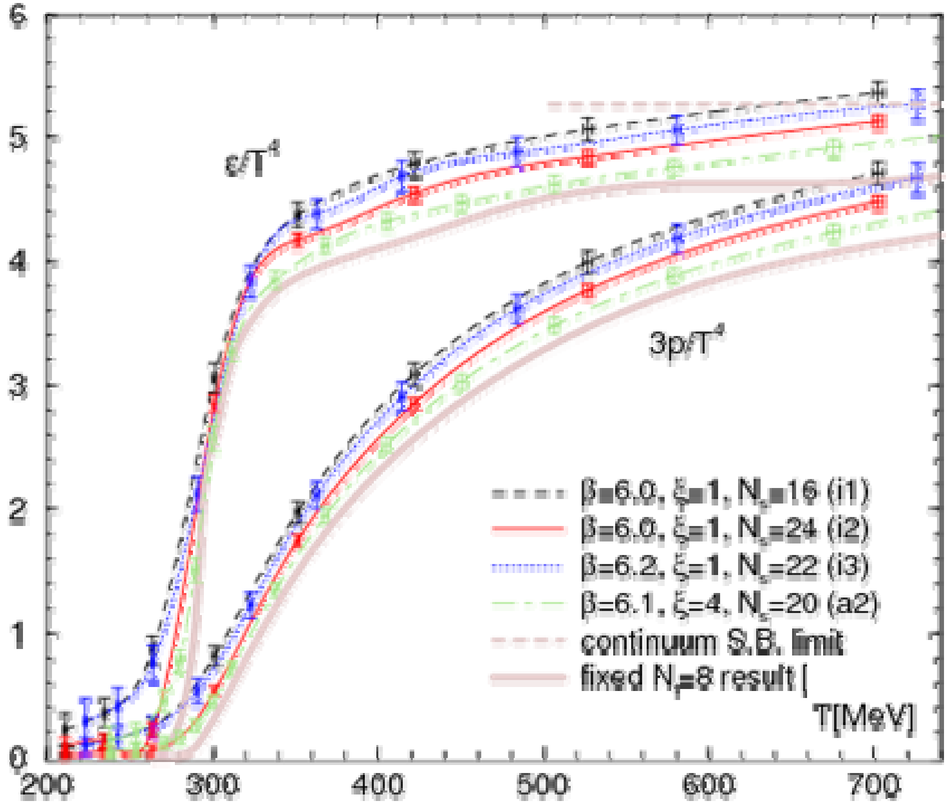
beta function : obtained by r_0/a_s fit
r_0/a_sdata H.Matsufuru et al. ('01)

$\frac{\partial \xi_0}{\partial \beta}\Big|_\xi$ is required
in SU(3) gauge theory.

→ T.R.Klassen ('98)

- Anisotropic lattice is useful
to increase Temp. resolution.

Pressure & Energy density



- Integration $\left(\frac{p}{T^4} = \int_0^T dT' \frac{\epsilon - 3p}{T'^5}\right)$

  is performed with the cubic spline of (e-3p)/T^4

- Cubic spline vs trapezoidal inte. yields small difference ~ 1σ

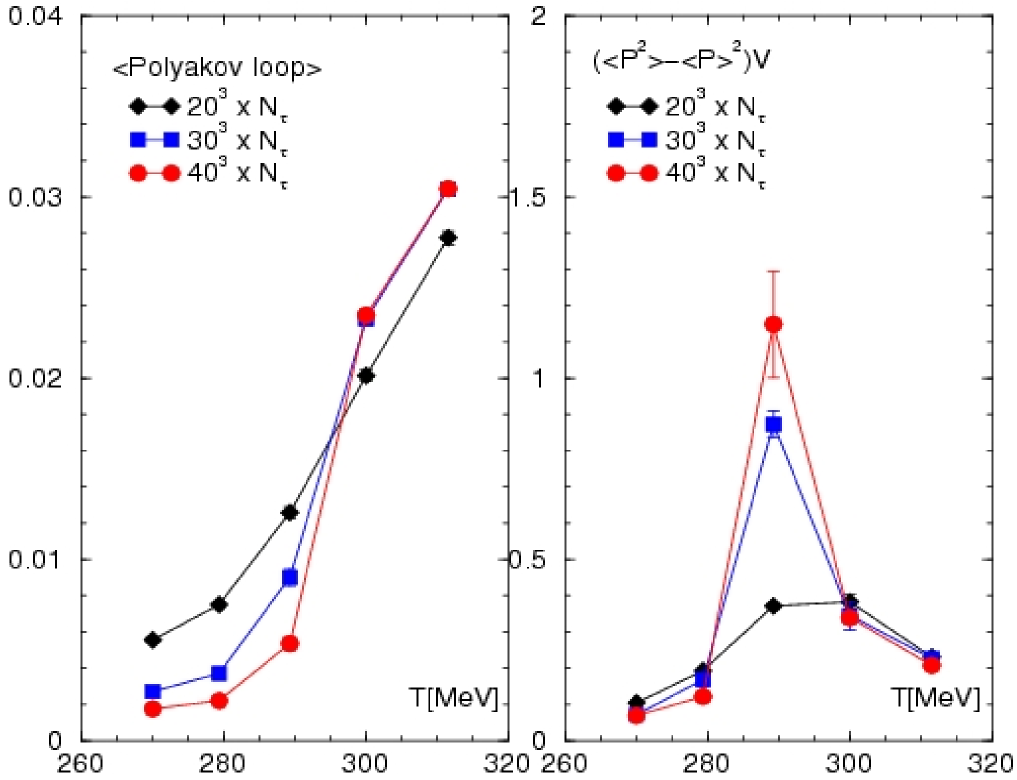
- Our results are roughly consistent with previous results.

- Unlike the fixed N_t approach, scale/temp. is not constant.

→ Lattice artifacts increase as temperature increases.

Our fixed scale approach with "T-integration method" works well !!

Transition temperature at fixed scale

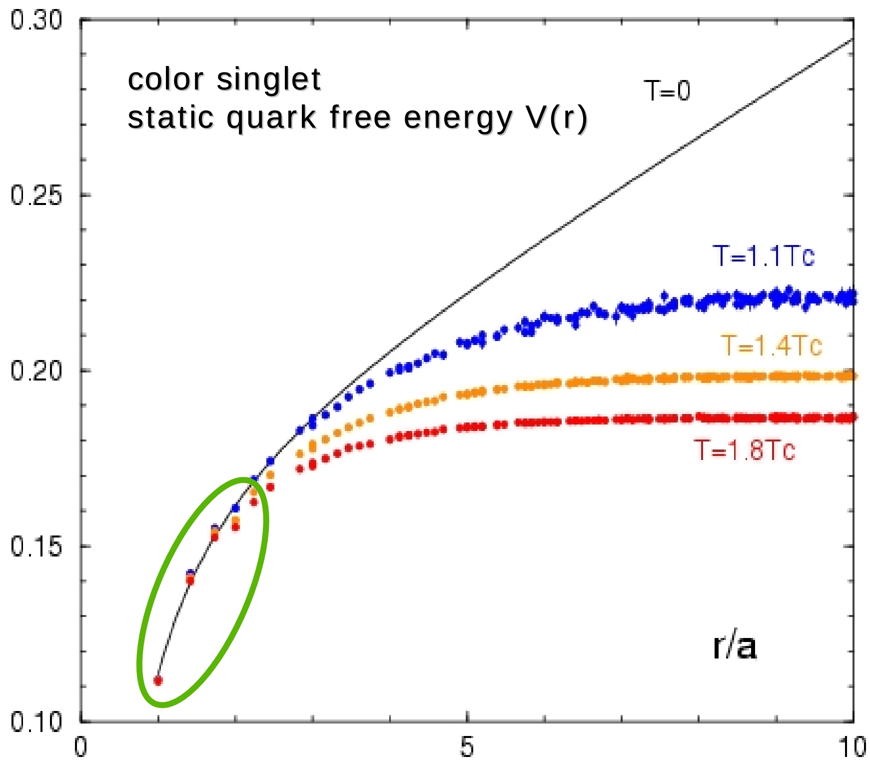


T-dependence of the (rotated) Polyakov loop and its susceptibility

- No renormalization is required upto overall factor due to the fixed scale.
- Rough estimation of critical temperature is possible.

T_c = 280~300 MeV at β =6.1, ξ =4 (SU(3) gauge theory)

Static quark free energy at fixed scale



Static quark free energies at fixed scale

- Due to the fixed scale, no renomalization constant is required.

→ small thermal effects in V(r) at short distance (without any matching)

- Easy to study temperature effect of V(r) without scale & volume effects

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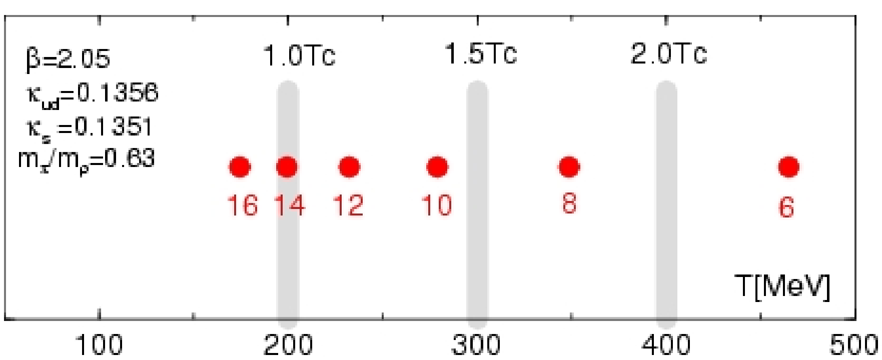
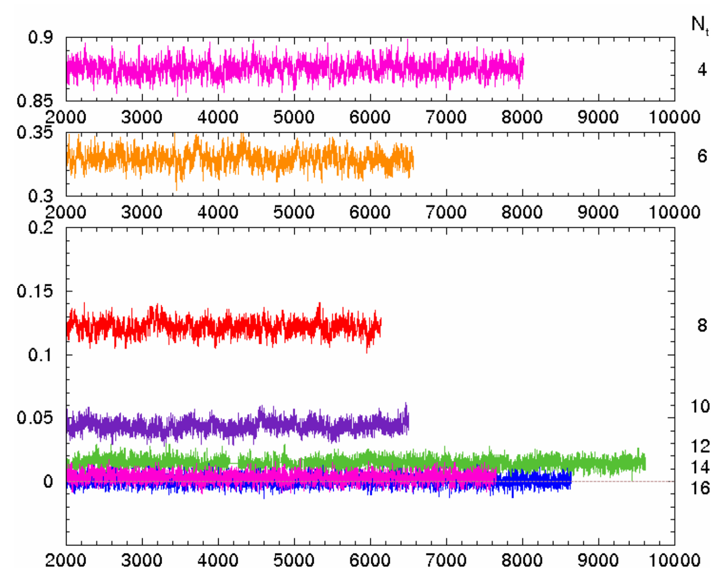
Toward the EOS in N_f=2+1 QCD

- Basic T=0 simulation:
  CP-PACS / JLQCD Collab. N_f=2+1 study *Phys. Rev. D78 (2008) 011502.*
  - RG-improved Iwasaki glue + NP clover-improved Wilson quarks
  - $(2\ \mathrm{fm})^3$ lattice, a=0.07, 0.1, 0.12 fm
  - $m_{ps}/m_v(LL)$~0.63—0.77, $m_{ps}/m_v(SS)$~0.68—0.75
  - configurations available on the ILDG
- T>0 simulations: on $32^3 \times N_t$ (N_t=4, 6, ..., 14, 16) lattices

Nt's correspond to T~170—700MeV





Summary

- We adopt Fixed scale approach
  to study Hot (& dense) QCD with Wilson-type quarks

  T-integral method to study EOS works well in quenched QCD

- We have already generated T>0 configurations
  using CP-PACS/JLQCD parameter

  (N_f=2+1 Clover+RG, 1/a=3GeV, pion mass ~ 500MeV)

- Our final goal is to study thermodynamics on
  the physical point (pion mass ~ 140MeV)
  with N_f=2+1 Wilson quarks (PACS-CS)
  or exact chiral symmetry with N_f=2+1 Overlap quarks (JLQCD)

- We are looking for new ideas to study other physics on our config.

  (density correlations, J/psi suppression, finite density...)