2015/09/05
CCS

The Structure of the Vacuum and Conformal Properties in High Temperature QCD

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In Collaboration with

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Yu Nakayama(Caltech & IPMU)

T. Yoshie(U. Tsukuba)

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Phys.Rev. D89 (2014) 114503
Phys. Lett. B748(2015) 269

Plan of Talk

Introduction

Phase structure; existence of conformal region

Conformal theory with an IR cutoff

Structure of the vacuum; twisted Z(3) vacuum

Scaling relation of effective masses

Continuum limit and thermodynamical limit at small g

non-perturbative effects at larger g

Implications for physics

A fundamental issue at high temperature QCD

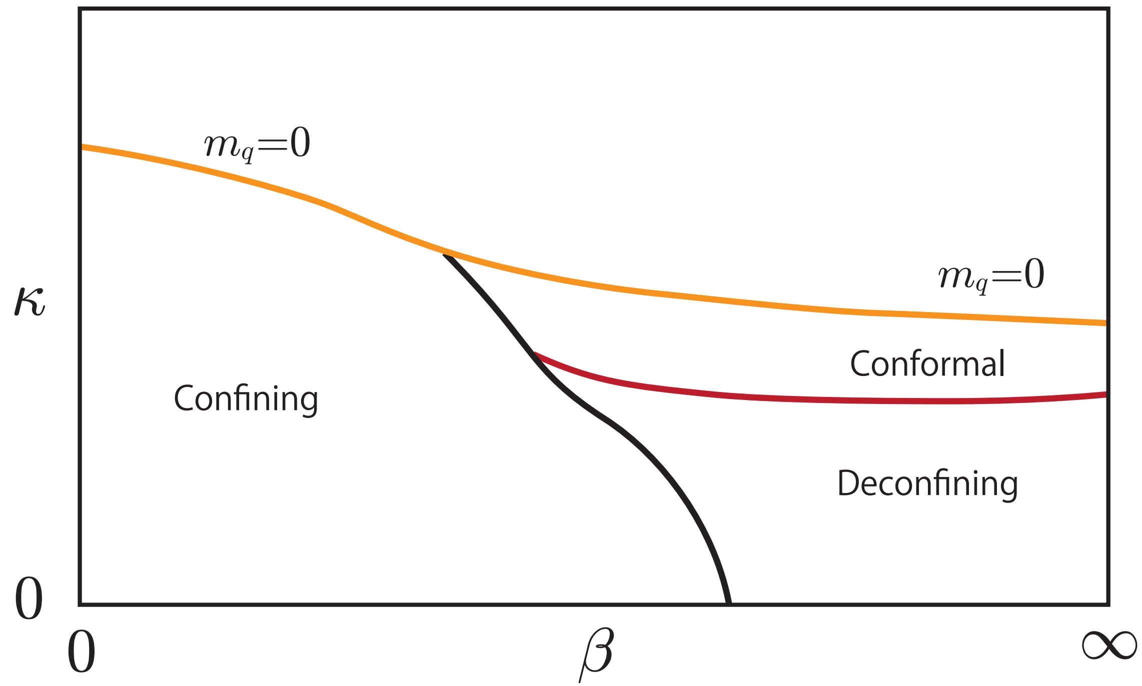
what kind of state the gluons and quarks take
at high temperatures ?

Our claim: Existence of Conformal Region

$N_f \leq 6$

$m_q \leq \Lambda_{IR}$

IR cutoff



the vacuum is a Z(3) twisted vacuum modified by non-perturbative effects

PS propagators behave at large t with modified Yukawa- type decay form instead of exponential decay form.

Stage and Tools

SU(3) gauge theories with Nf=2 in the fundamental representation

Action: the RG gauge action and Wilson fermion action

Lattice size: 32^3 x 16

Aspect ratio r = L/L_t = N/N_t = 2

Boundary conditions: periodic boundary conditions

an anti-periodic boundary conditions (t direction) for fermions

Algorithm: Blocked HMC

Statistics: 1,000 +1,000 ~ 4000 trajectories

Computers: U. Tsukuba: CCS HAPACS; KEK: HITAC 16000

Continuum limit

Define gauge theories as the continuum limit of lattice gauge theories

$N_x = N_y = N_z = N$ $N = rN_t$ (r aspect ratio) r= 2 in this work

take the limit a->0 and N -> infinity

with $L = aN$ and $L_t = aN_t$ fixed

when L and/or Lt finite => IR cutoff

Conformal theories:
IR cutoff: an indispensable ingredient
in contrast with QCD

Thermodynamical Limit

$L \to \infty$

Keeping $T = 1/(N_t a)$ constant

Conformal theory with an IR cutoff

PRD87, 89

A running coupling constant $g(\mu; T)$

the IR fixed point $g^*(\frac{1}{N_T T}; T)$

IR cutoff T

RG argument

$m_q \leq \Lambda_{IR}$ Conformal region

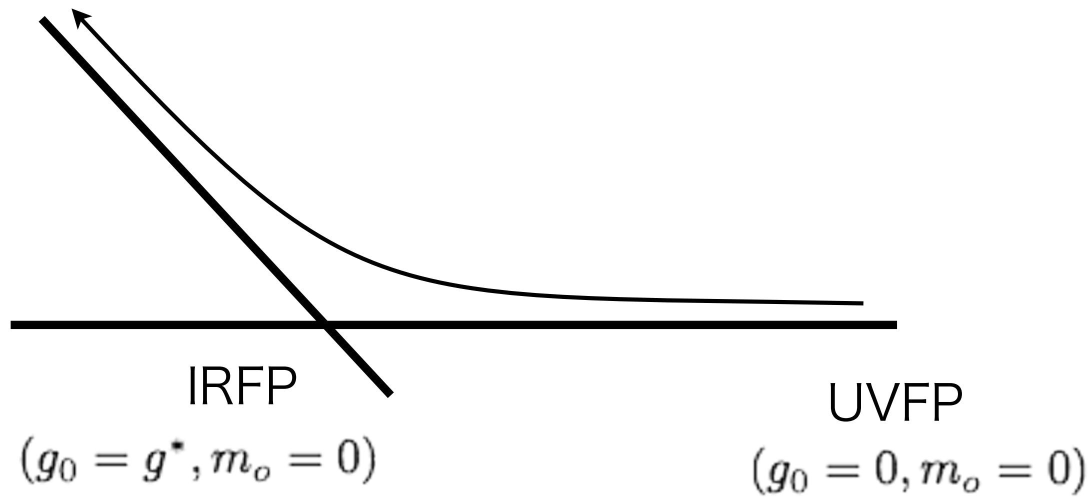
RG scaling relation

Extension of the scaling relation → the IR fixed point

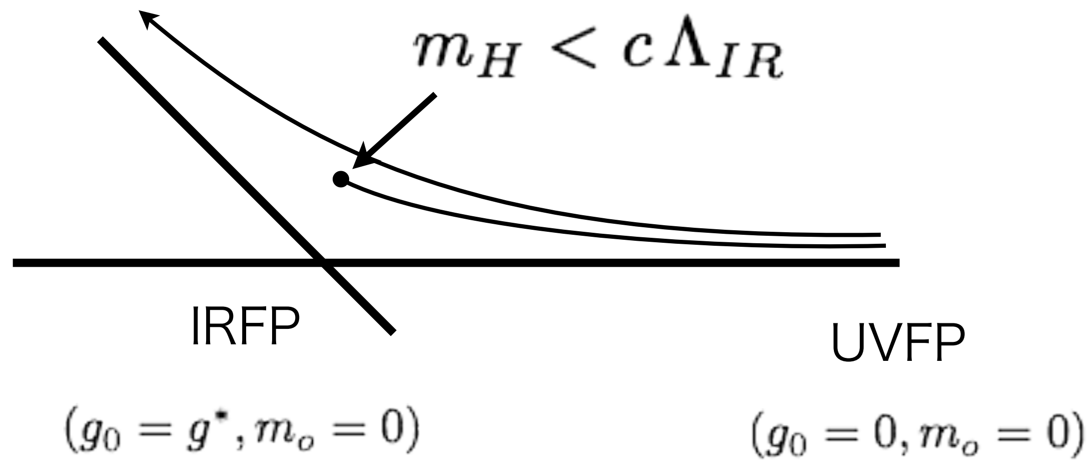
PLB

RG argument

When $\Lambda_{IR} = 0$



When $\Lambda_{IR} = finite$



Z(3) Symmetry

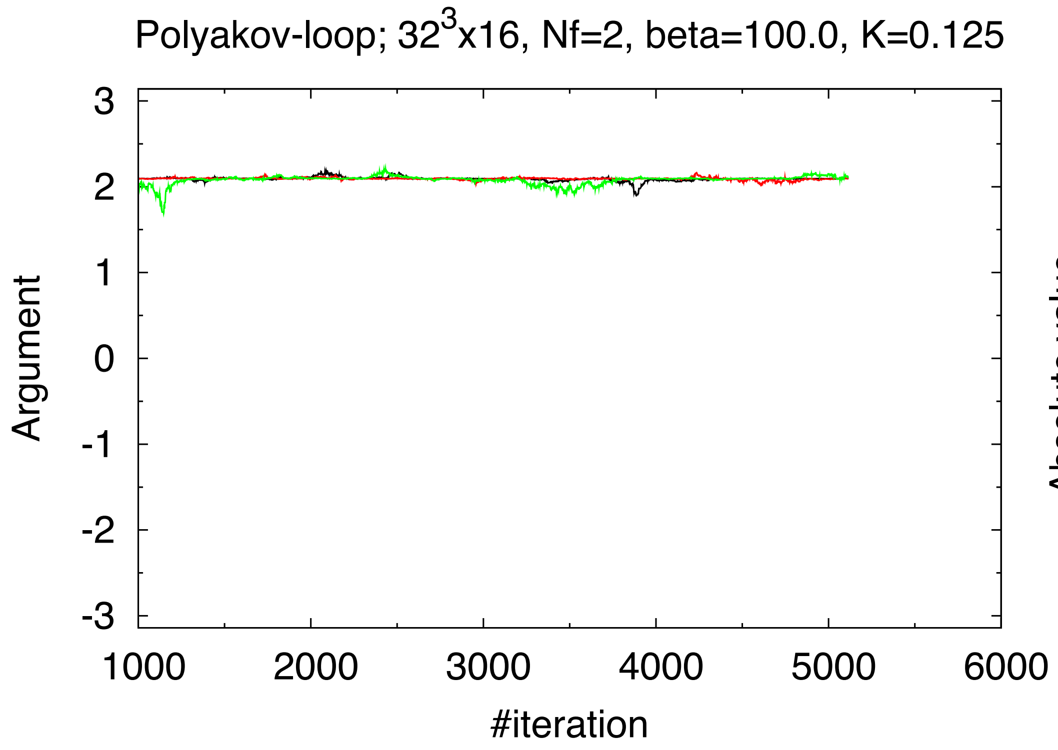
satisfied at g=0; broken at g > 0

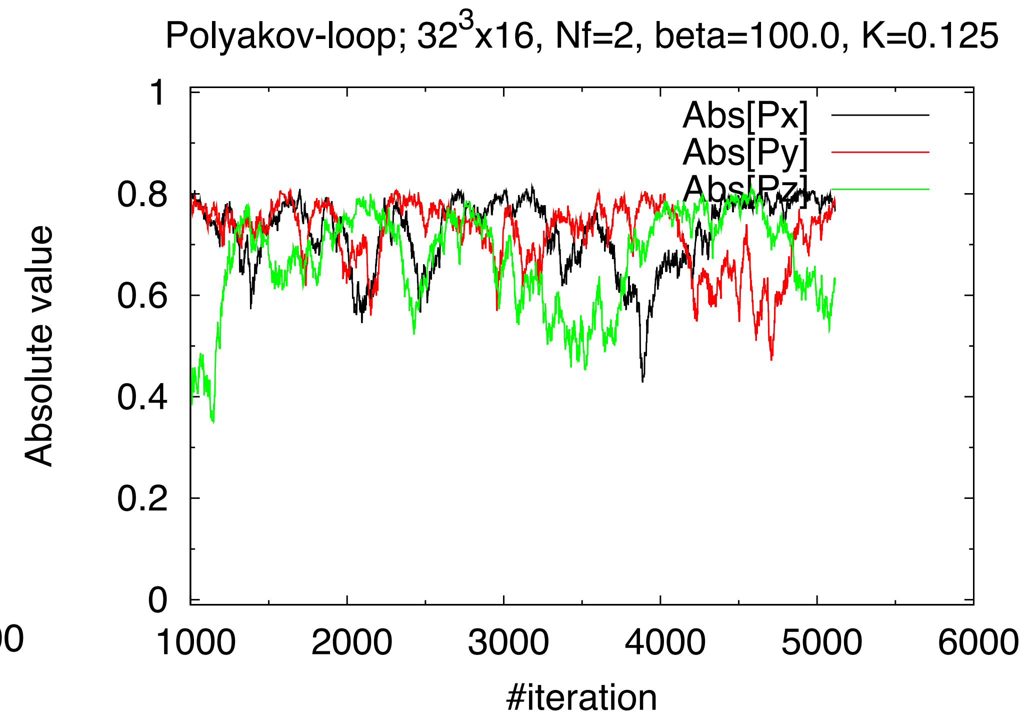
one-loop calculation in term of Polyakov loops in spacial directions on a finite lattice

$$U_i = \mathrm{diag}(e^{i2\pi a_i}, e^{i2\pi b_i}, e^{i2\pi c_i})$$

mq=0.0 : The lowest energy state ~	$\exp(\pm i2/3\pi)$	$\exp(\pm i2/3\pi)$	$\exp(\pm i2/3\pi)$
The second lowest energy state ~	$\exp(\pm i2/3\pi)$	$\exp(\pm i2/3\pi)$	1
The third lowest energy state ~	$\exp(\pm i2/3\pi)$	1	1
unstable state ~	1	1	1
mq > 1.0 stable state ~	1	1	1

polyakov loops; beta=100.0, K=0.125





2\pi/3=2.09

magnitude ~ 0.8

Z(3) twisted vacuum

modified by non-perturbative effects

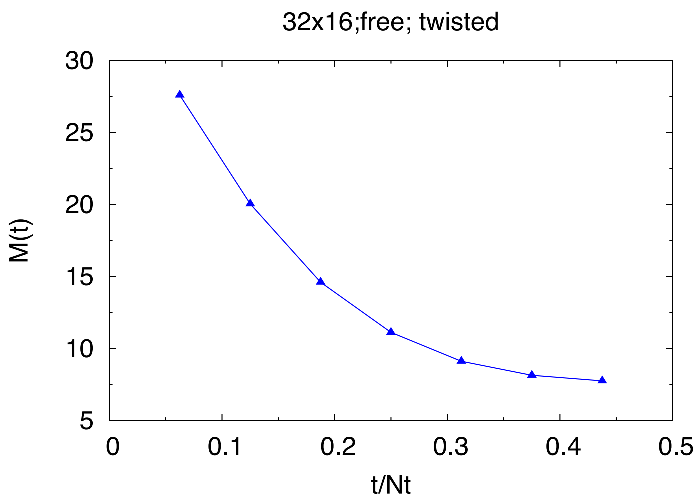
Scaled effective masses of PS propagators

$$\mathfrak{m}(\tau, N, N_t) = N_t M(\tau, N, N_t) \qquad \tau = t/N_t$$

$$M(t) = \ln \frac{G(t)}{G(t+1)}$$

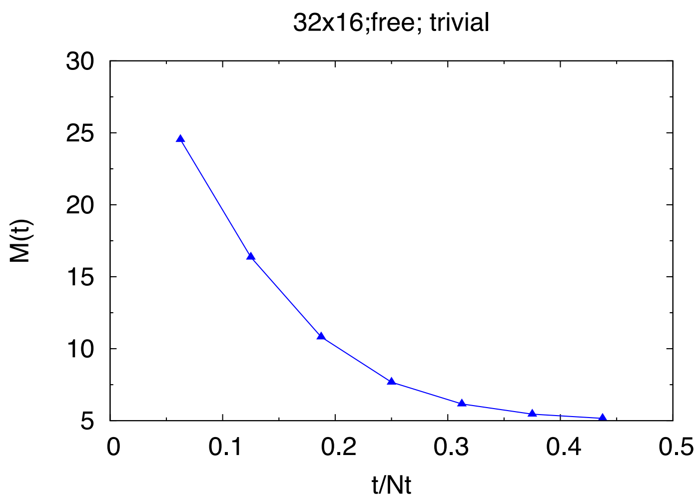
twisted vacuum

32x16



trivial vacuum

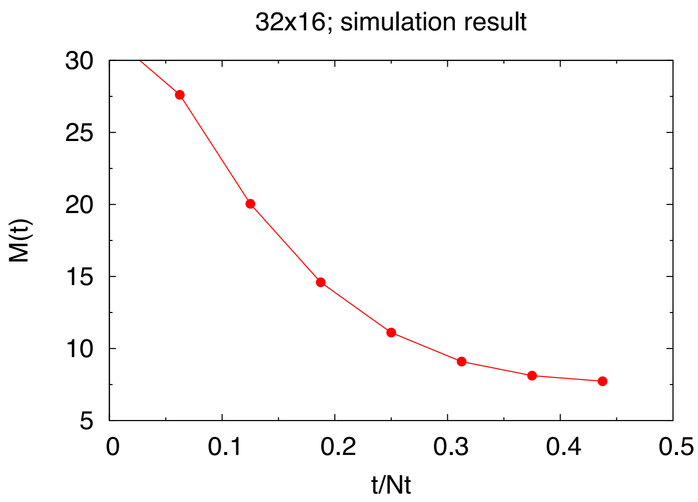
32x16



Scaled effective masses

simulation result
beta=100.0

32x16

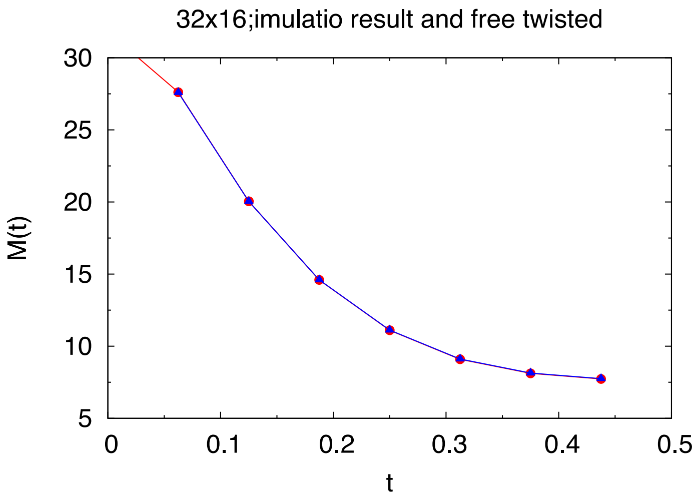


Scaled effective masses

overlapped with simulation result

twisted vacuum

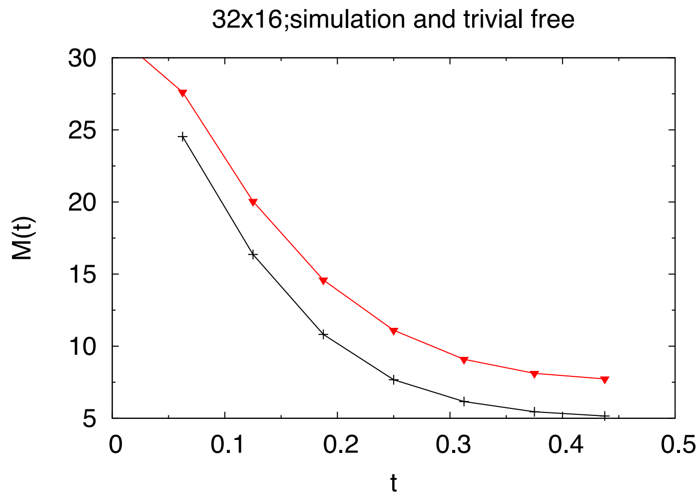
32x16



overlapped completely

trivial vacuum

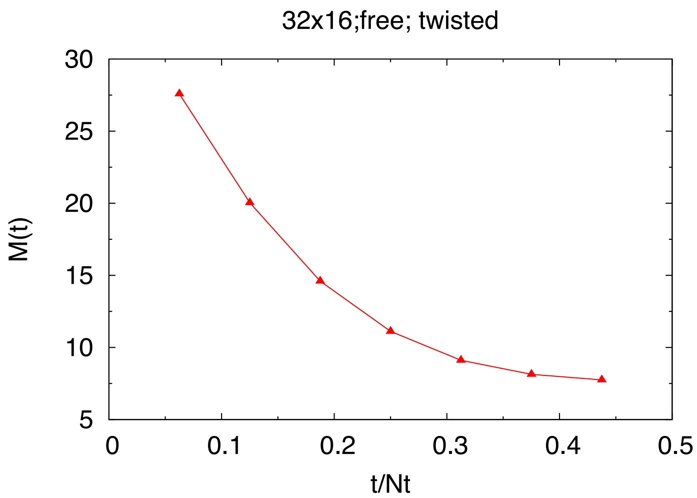
32x16



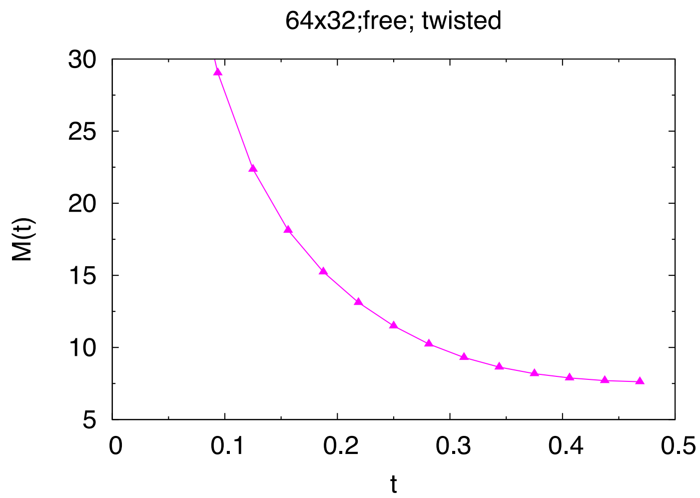
Scaling law of scaled effective masses

$$\mathfrak{m}(\tau, N, N_t) = \mathfrak{m}(\tau, N^{'}, N_t^{'})$$

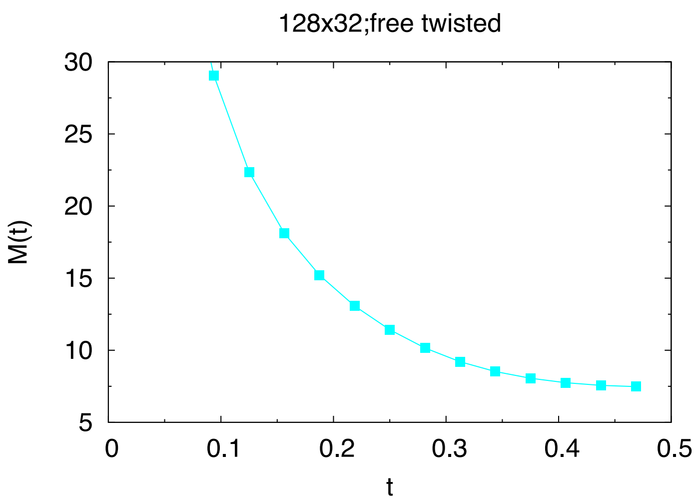
32x16



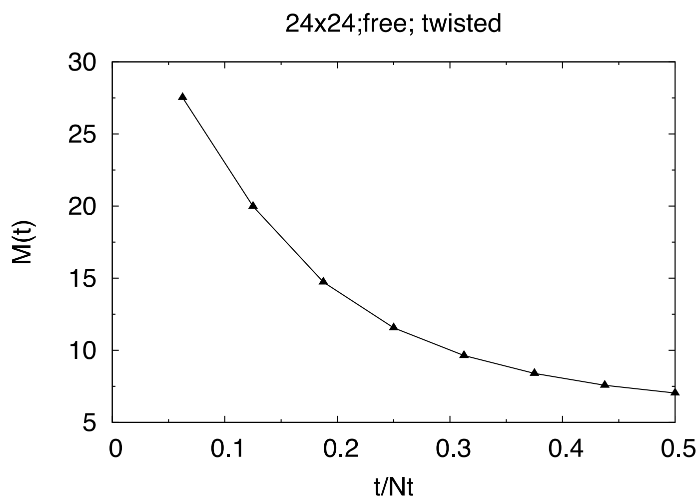
64x32



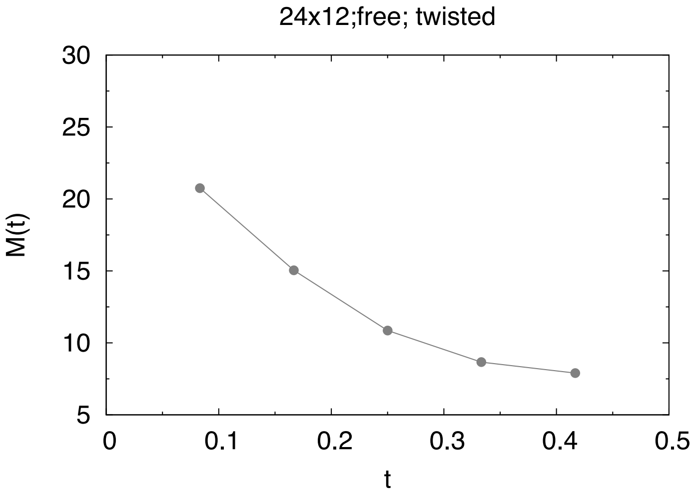
128x32



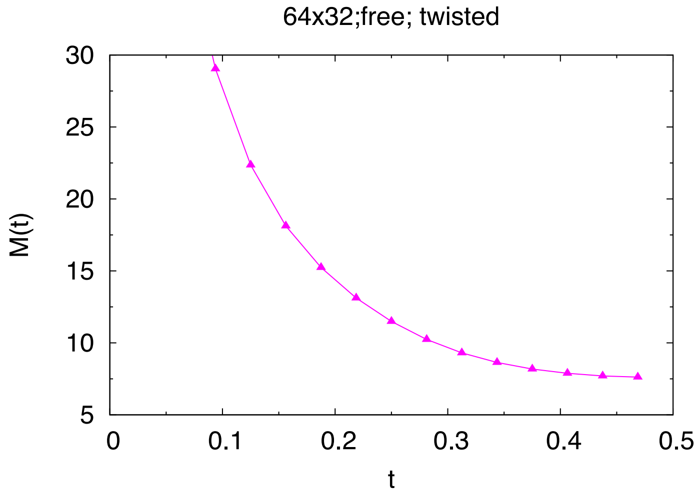
24x24



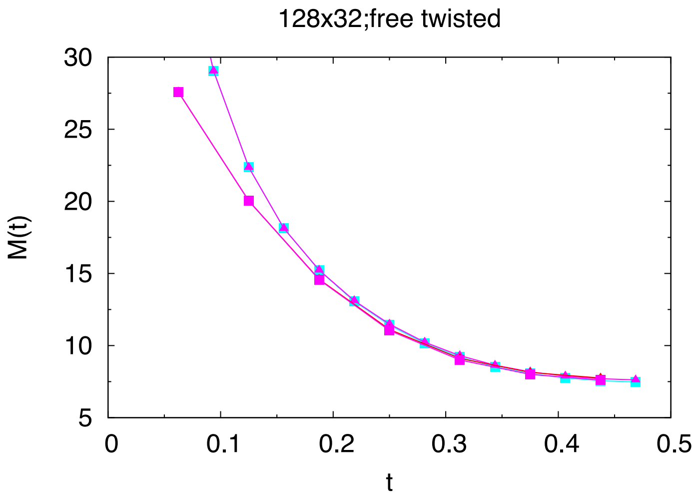
24x12



64x32



128x32; 64x32; 32x16; 64x16



Scaling law enables us to take the both limits

Continuum limit

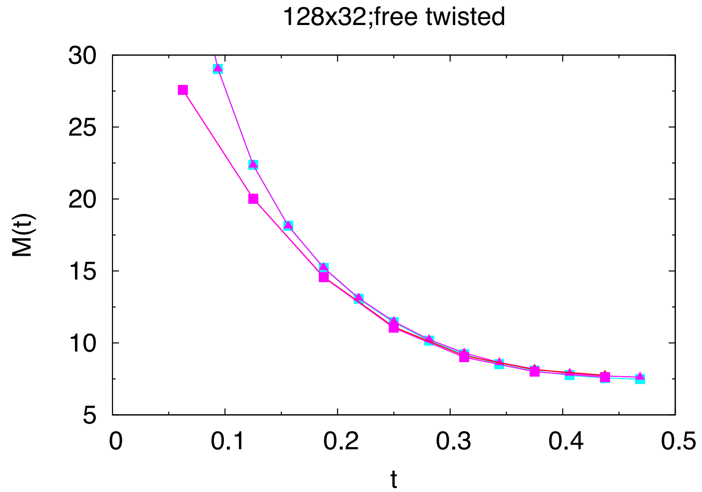
N -> infiity, Nt-> infinity L= const Lt= constant r=N/Nt= constant

Thermodynamical limit

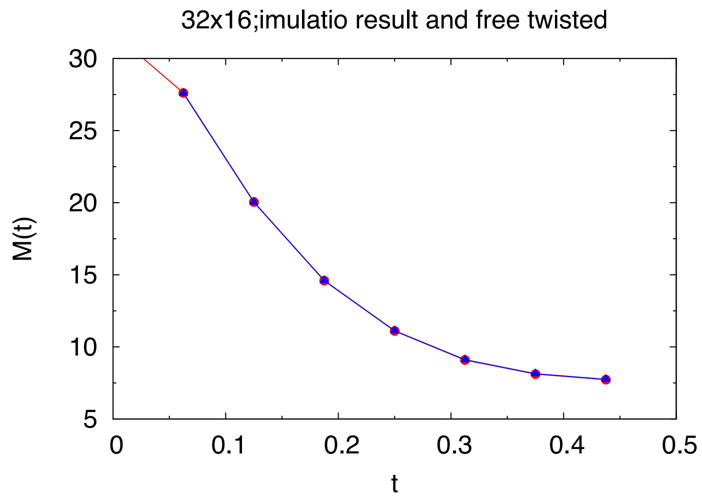
L-> infinity with Lt=constant

effective mass plot is independent of T

y-axis scale: temperature T

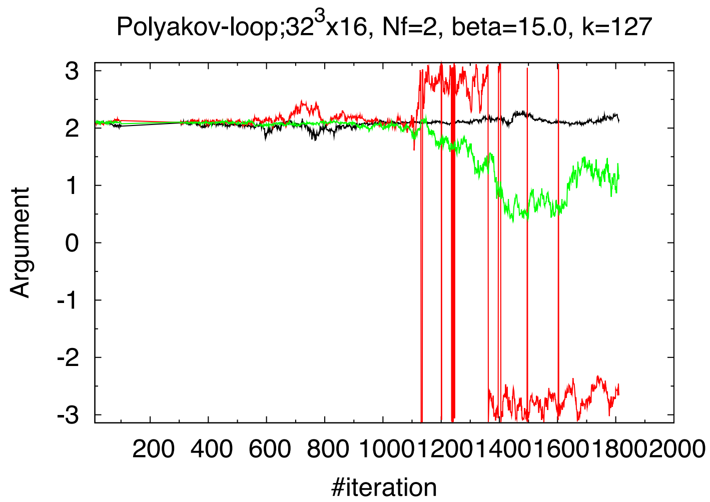


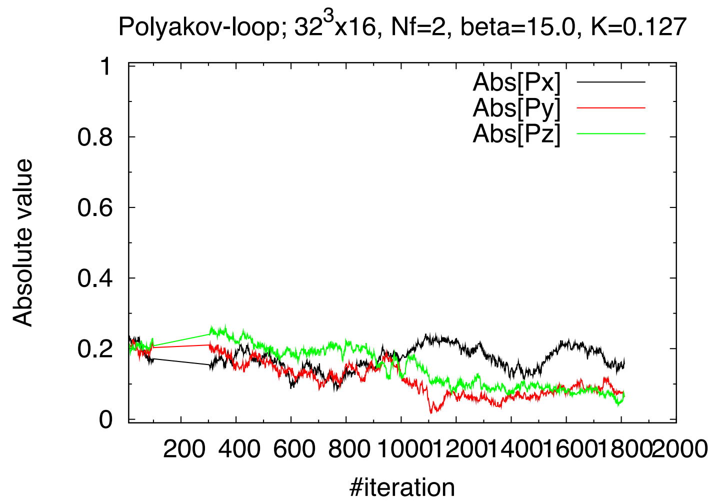
simulation result on 32^3 x16 for \tau > 0.2
well represents the result in the continuum limit
and in the thermodynamical limit



Along the massless line

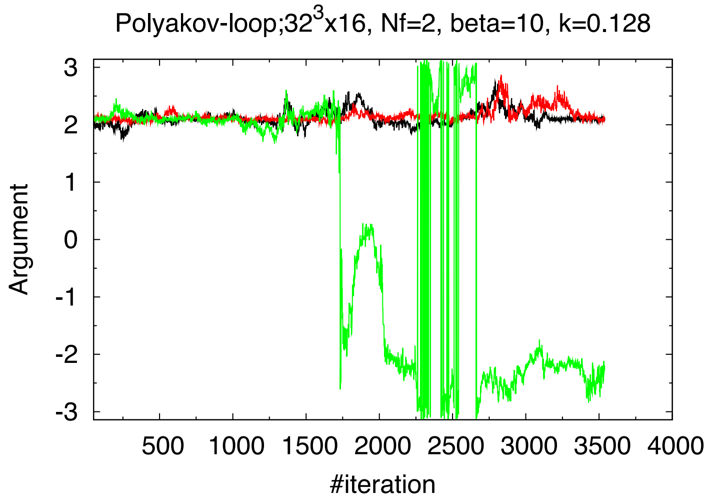
beta=15.0

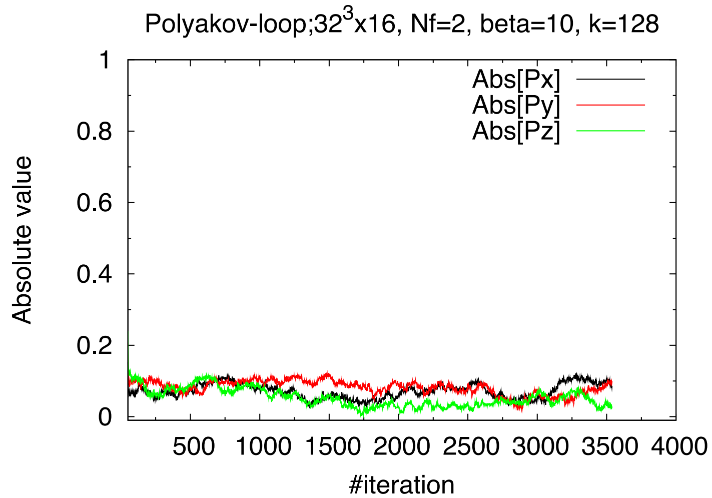




Along the massless line

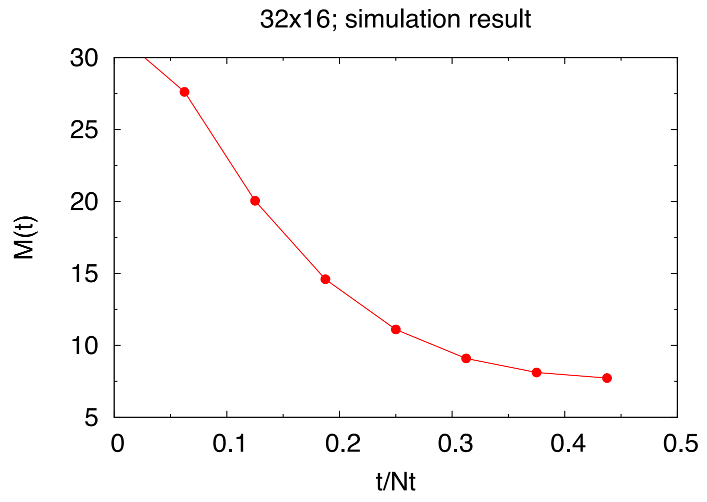
beta=10.0



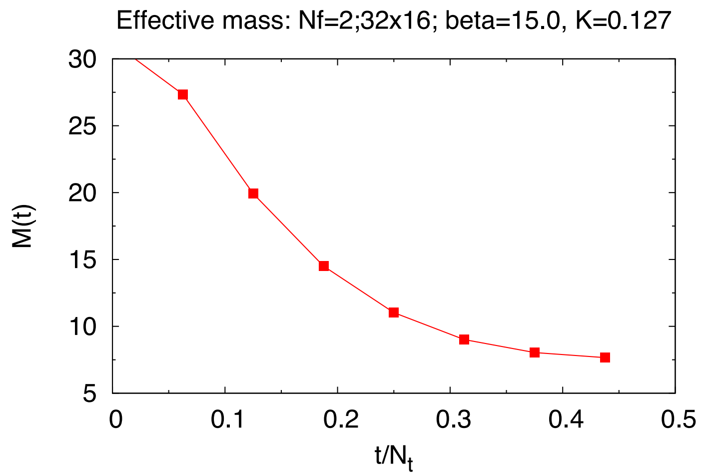


Along the massless line

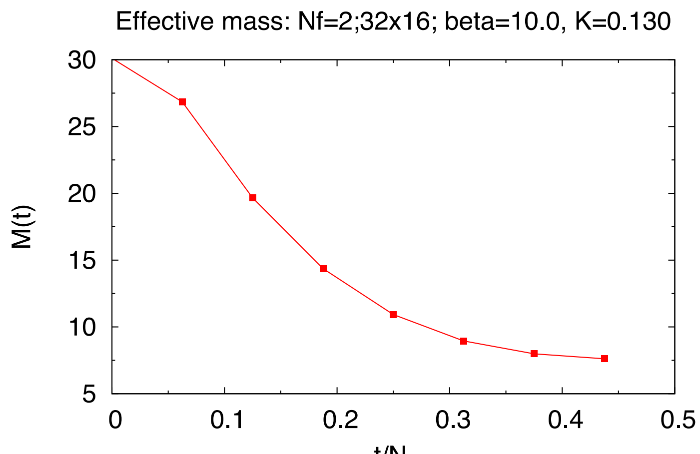
beta=100.0



beta=15.0



beta=10.0



Along the massless line

As g becomes larger non-perturbative effects larger

The Z(3) twisted structure and Conformal behavior remain

Remarks

the free massless fermion system is a typical example of conformal theory irrespective of the structure of vacuum

if the system is analytically connected with the massless fermion, it will exhibit conformal properties

Implications for physics

At very high temperature quarks and gluons are free particles not in the trivial vacuum but in the Z(3) twisted one. The very slow approach to Stefan Boltzmann ideal gas is due to that the vacuum is not the trivial vacuum and the nonperturbative effects do not disappear even at large beta

In a conformal theory with an IR cutoff, the hyper-scaling relations is satisfied.
mPS = c mq^{1/(1+\gamma*) with \gamma^* the anomalous mass dimension.
Non-analytic behavior of the mPS in terms of the mq may be a solution of the recent issue whether the U(1) symmetry recovers at the chiral transition point for Nf=2

The existence and the dissociation of quarkonia at high temperature
may be related with the conformal state and deconfining state of the quarkonia.
The trasnsition occurs at the mass mPS ~ c T; c ~ 4 \pi

Thank you very much !

金谷さん

還暦おめでとうございます

金谷さんとの邂逅

1987-90　特別推進　QCDPAX

特別配置助手　公募

ハード・ソフトバグ洗い出し　丸１年

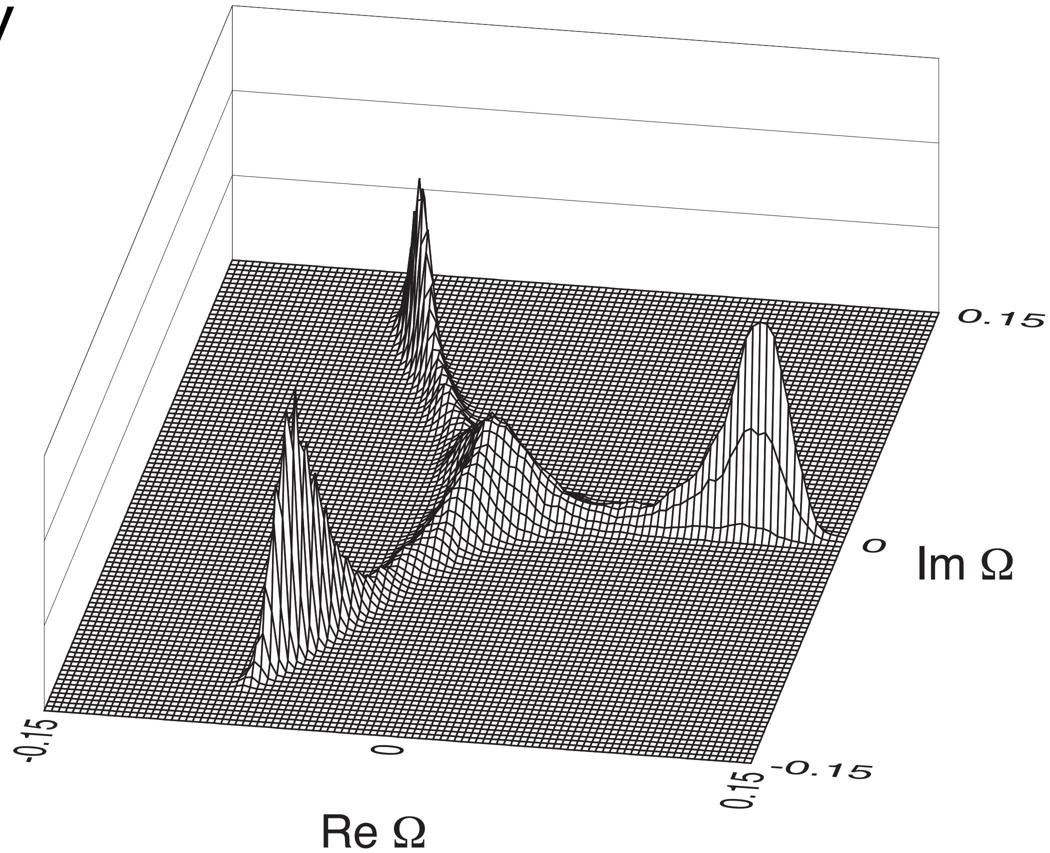
Pure SU(3) gauge theory

並列計算機のプログラミング
細心の注意：コピー

Z(3) symmetry

PRD 46 (1992) 4657

at phase transition point
3 (deconfining)+
1(confnement)



金谷さんとの邂逅-2

QCDPAX 打ち上げ

竹園 ＝＞並木　ボトル２本

金谷さんとの共著

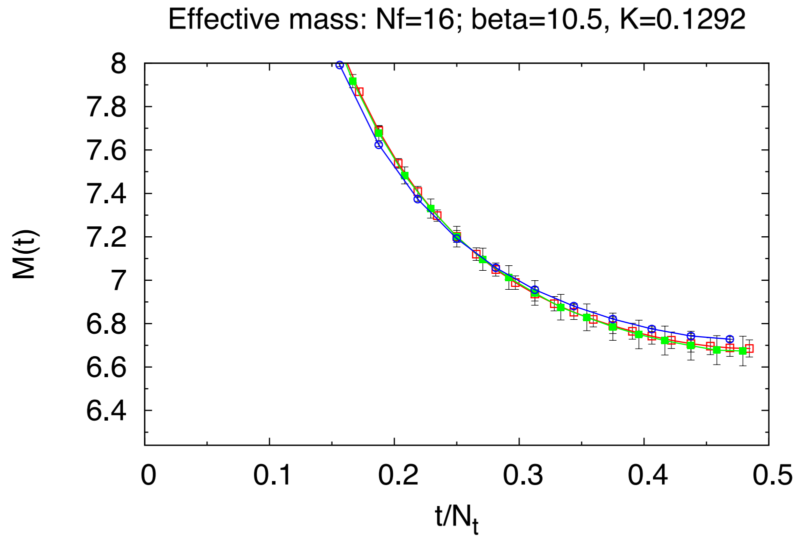
total 179

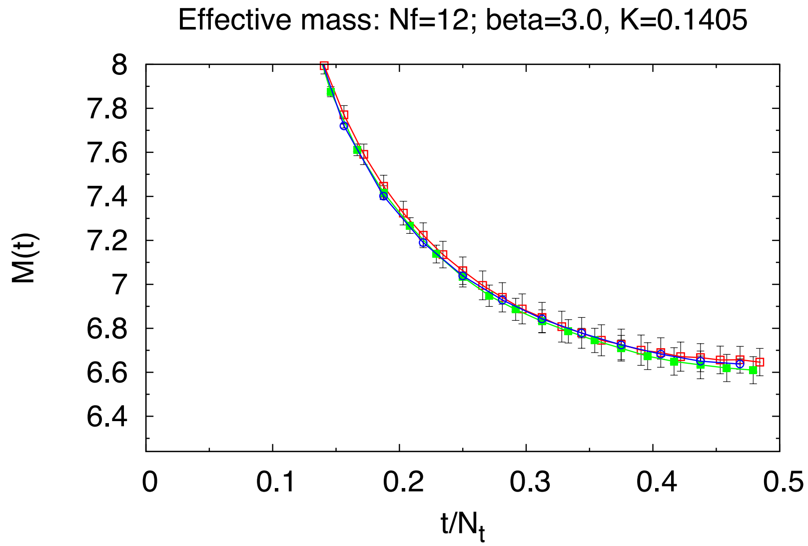
PRD 50

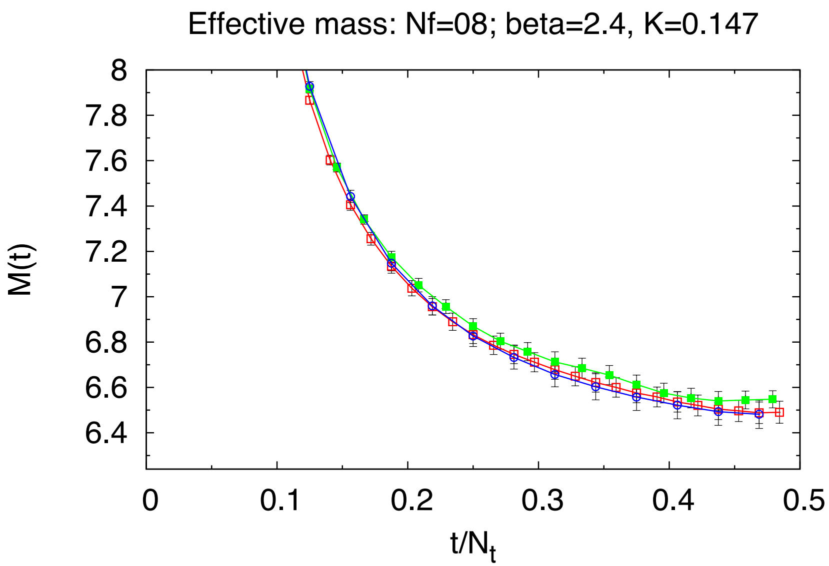
PRL 12

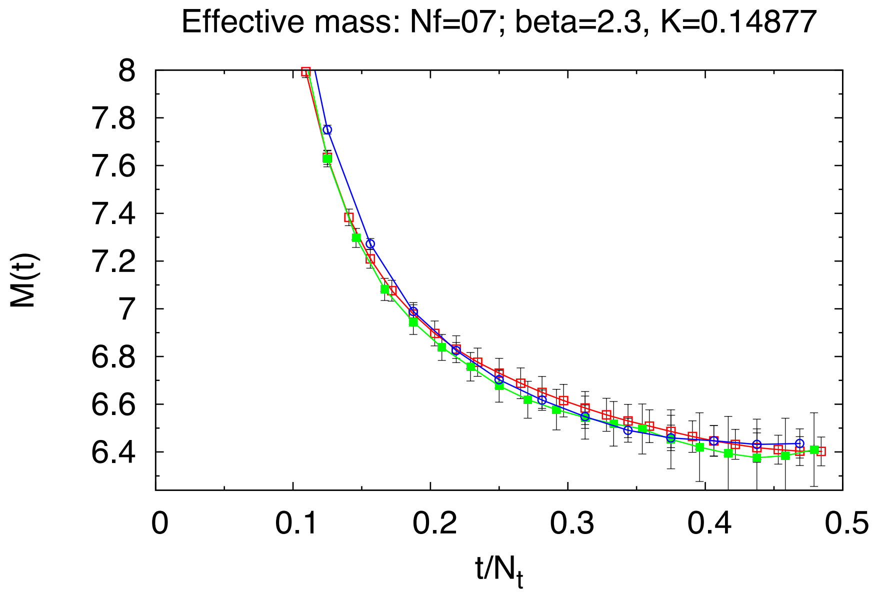
Scaling relation

$$\mathfrak{m}(\tau, N, N_t) = \mathfrak{m}(\tau, N^{'}, N_t^{'})$$


Effective mass: Nf=16; beta=10.5, K=0.1292
M(t)
t/N_t

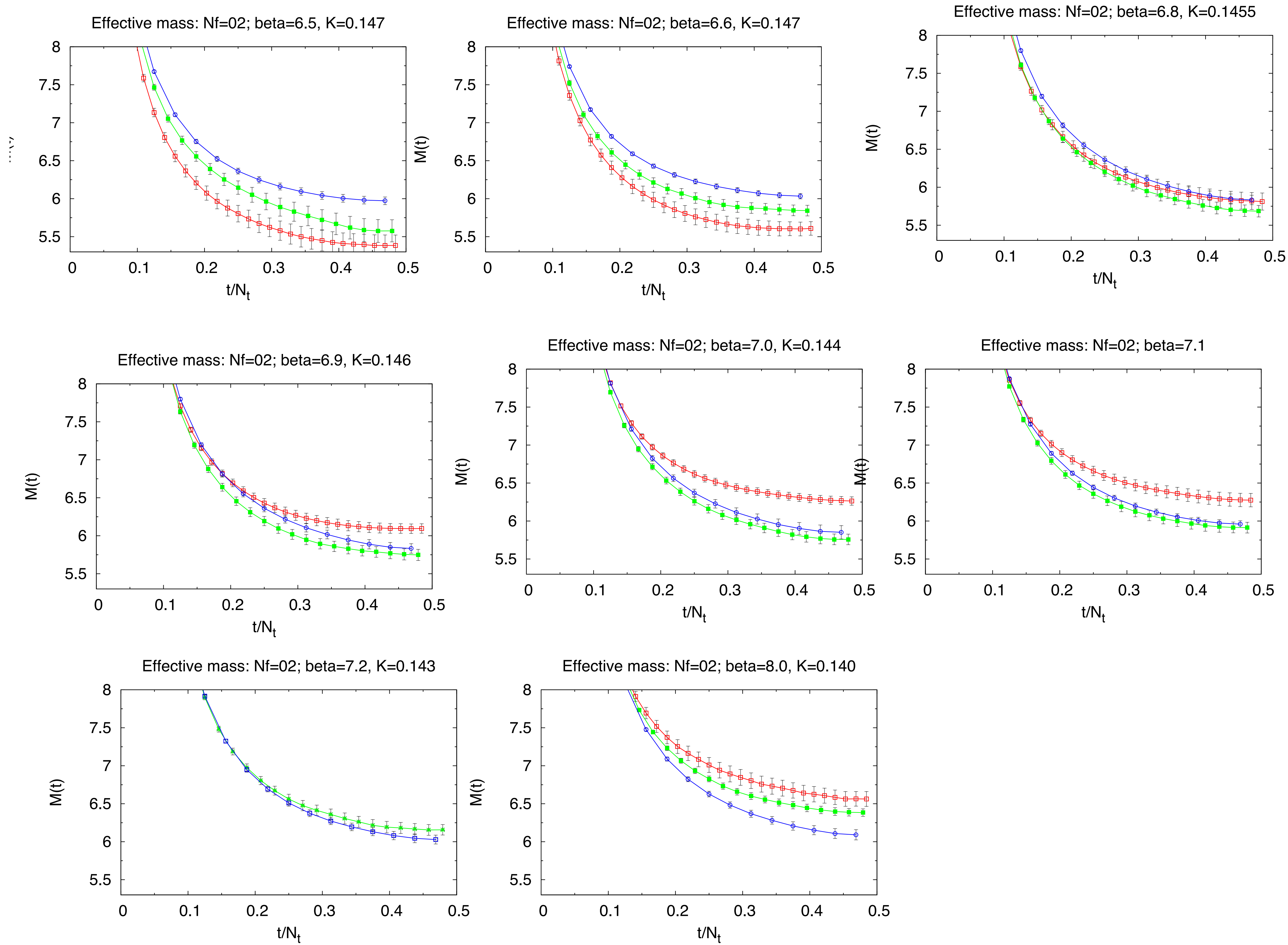

Effective mass: Nf=12; beta=3.0, K=0.1405
M(t)
t/N_t

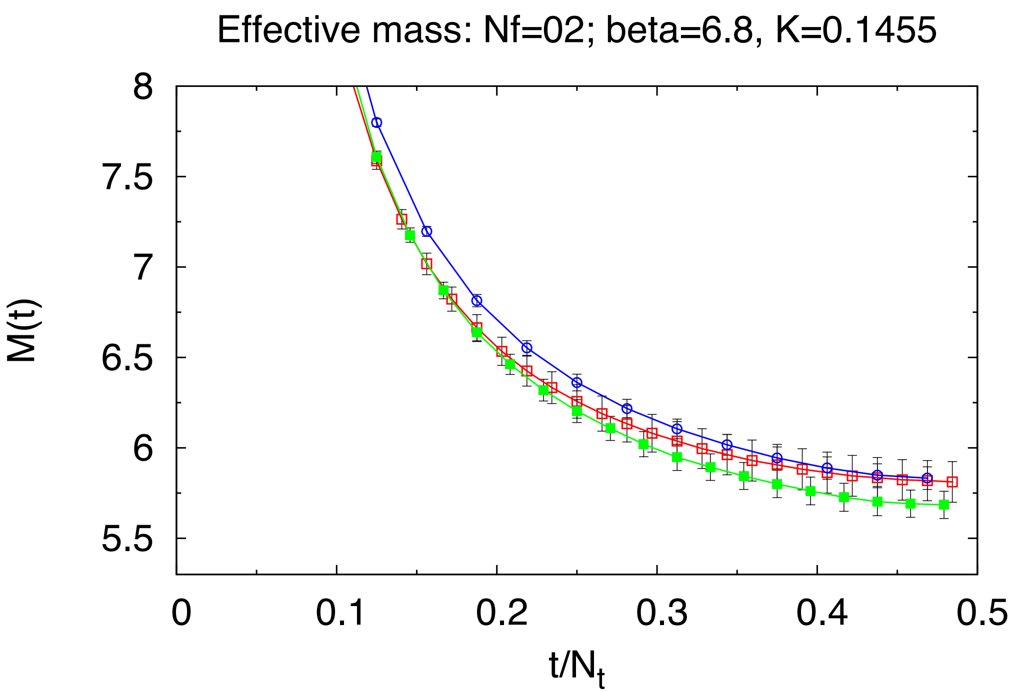

Effective mass: Nf=08; beta=2.4, K=0.147
M(t)
t/N_t

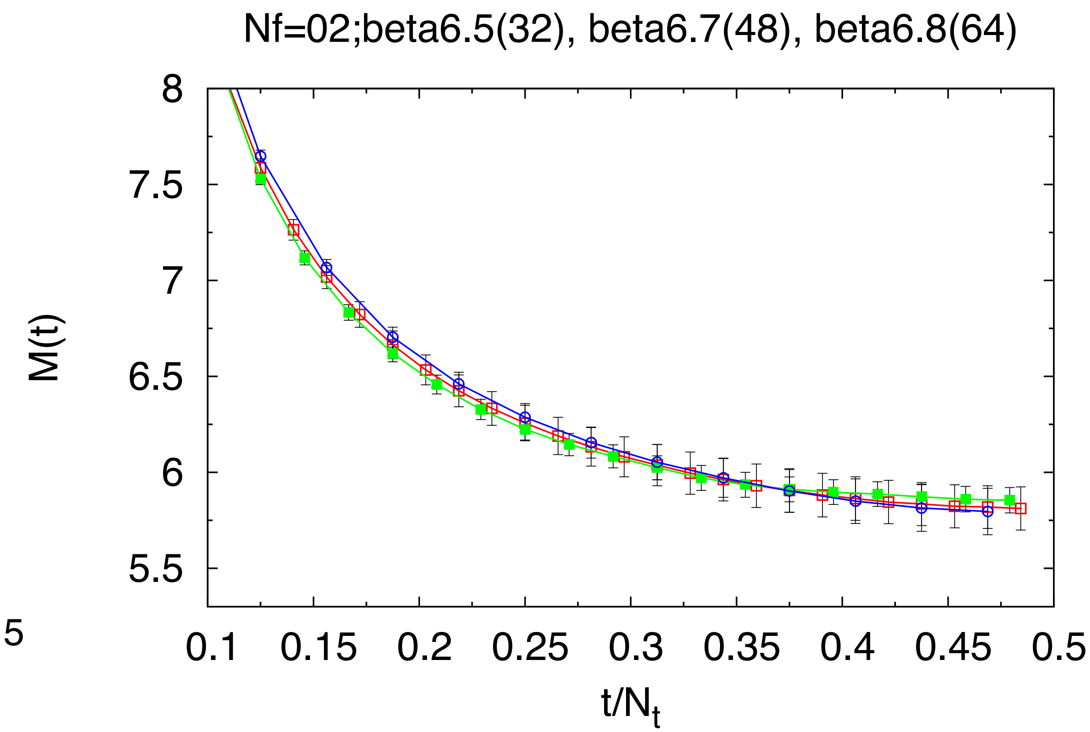

Effective mass: Nf=07; beta=2.3, K=0.14877
M(t)
t/N_t

RG scaling relation

$$\mathfrak{m}(\tau, \beta, N, N_t) = \mathfrak{m}(\tau, \beta^{'}, N^{'}, N_t^{'})$$


Effective mass: Nf=02; beta=6.5, K=0.147
Effective mass: Nf=02; beta=6.6, K=0.147
Effective mass: Nf=02; beta=6.8, K=0.1455
Effective mass: Nf=02; beta=6.9, K=0.146
Effective mass: Nf=02; beta=7.0, K=0.144
Effective mass: Nf=02; beta=7.1
Effective mass: Nf=02; beta=7.2, K=0.143
Effective mass: Nf=02; beta=8.0, K=0.140
M(t)
t/N_t


Effective mass: Nf=02; beta=6.8, K=0.1455
M(t)
t/N_t
8
7.5
7
6.5
6
5.5
0
0.1
0.2
0.3
0.4
0.5


Nf=02;beta6.5(32), beta6.7(48), beta6.8(64)
M(t)
t/N_t
8
7.5
7
6.5
6
5.5
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5