CONFORMALITY:

QCD with 8 and 12 flavors

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HISTORY : THE BANKS ZACS scenario

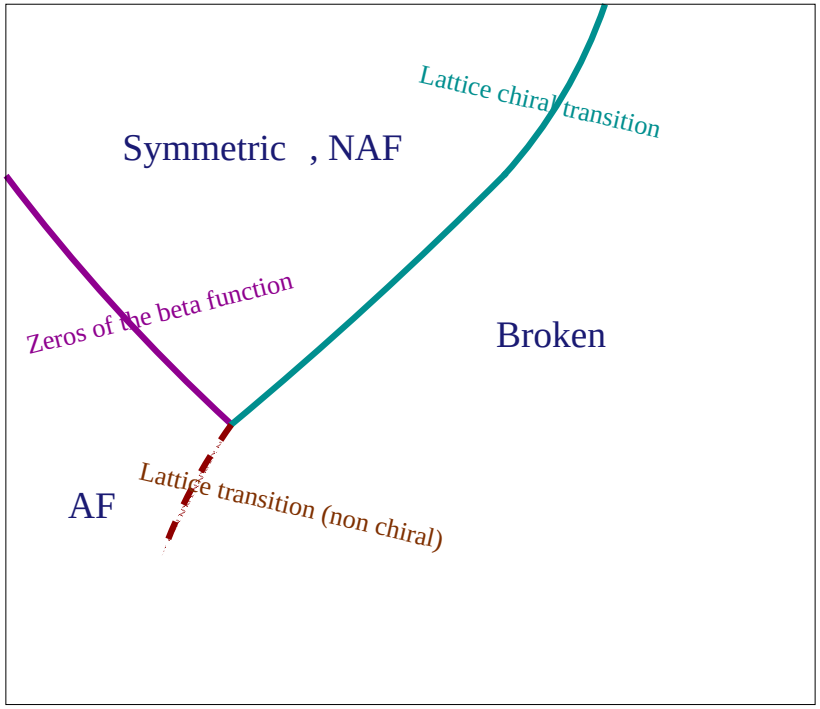
- With the N_f fermions in the fundamental representation , QCD is asymptotically free if:

$$N_f < \frac{11}{2} N$$

- At two loops, the theory has an infrared stable, non-trivial fixed point α^* if

$$\frac{34N^3}{13N^2+3} < N_f < \frac{11}{2} N$$

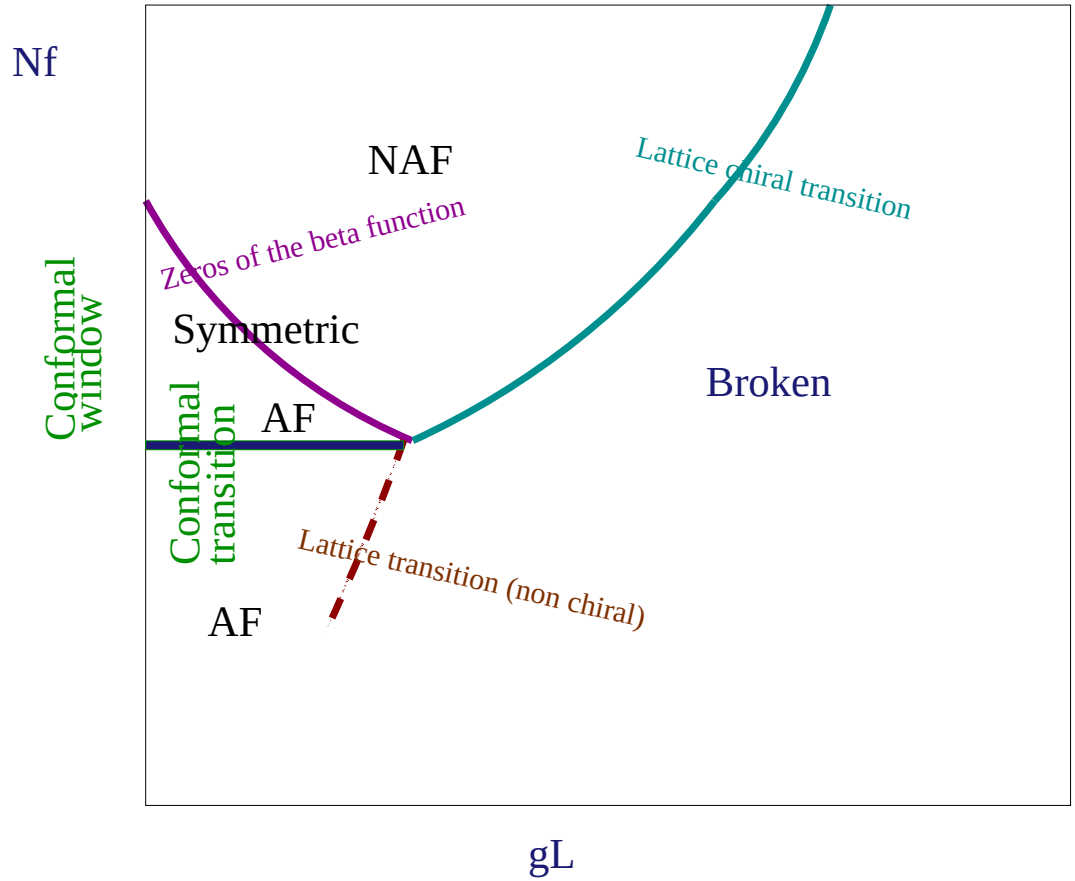
- If a zero, α_*, of the β function exists at two loops, it exists to any order in perturbation theory.
- For any N_f chiral symmetry is broken at large lattice coupling



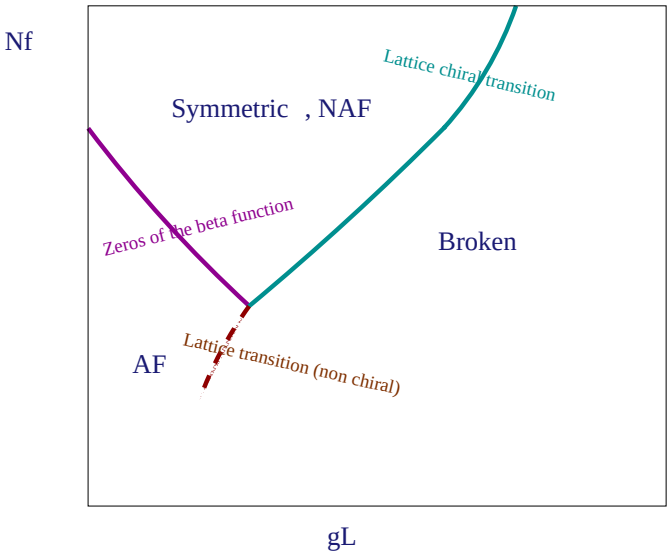
THE DISCOVERY OF THE CONFORMAL WINDOW OF QCD

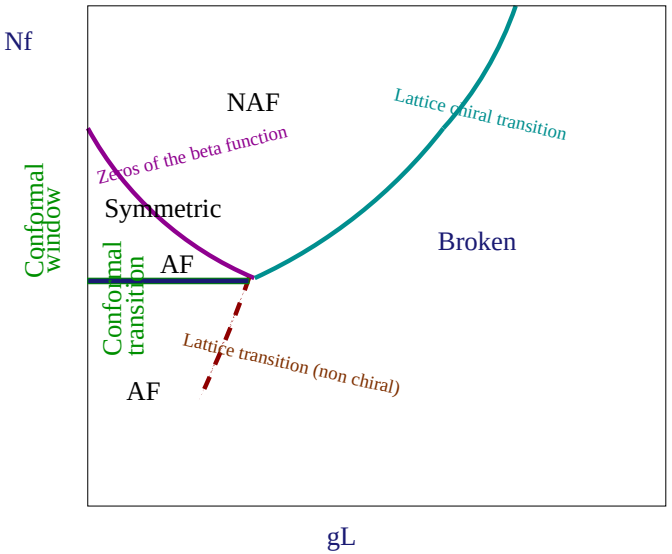
Appelquist et al. 1997

Mirasnky Yamawaki 1998 - Lattice phase diagram



- GOAL:
  - MAP OUT THE PHASE DIAGRAM
  - ESTABLISH CONTINUUM PROPERTIES
- CAVEAT :
  - SIMILARITIES BETWEEN THE CONFORMAL WINDOW AND A (COLD) PLASMA





PLAN

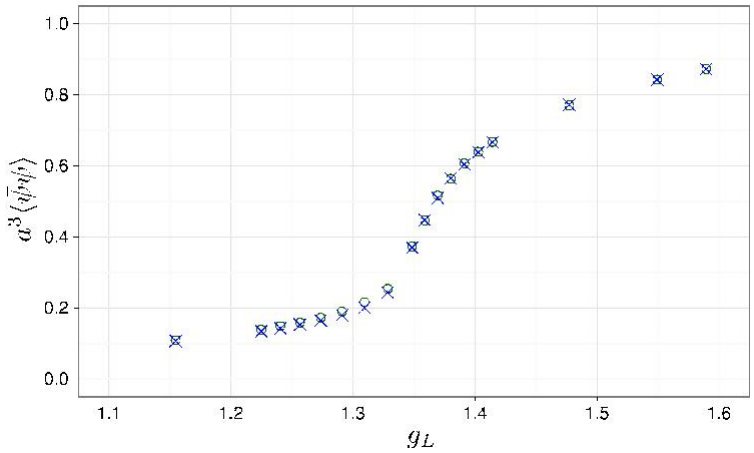
$N_f = 12$

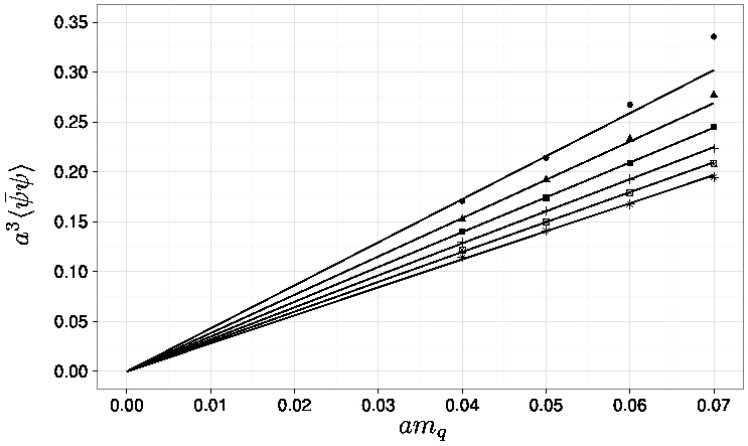
$N_f = 8$, and non-zero temperature

Summary

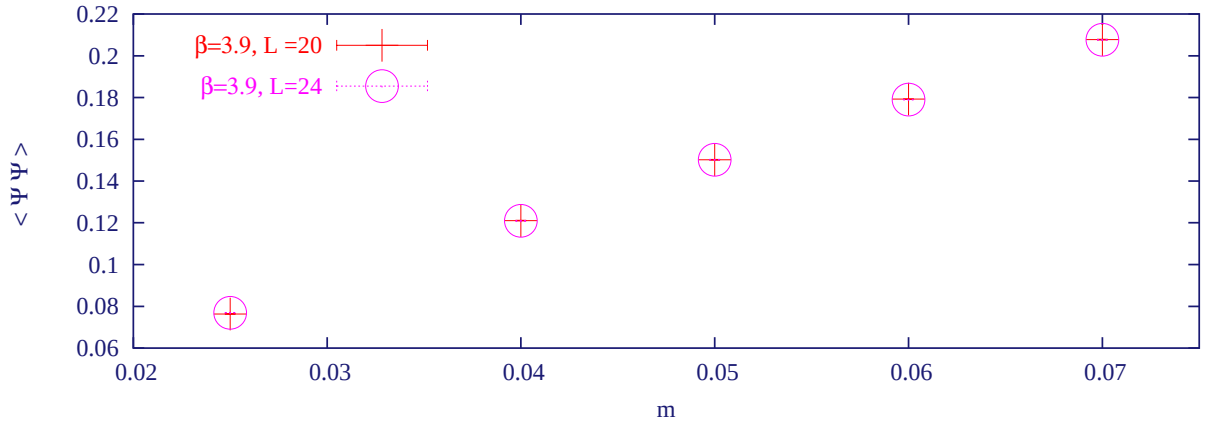
$$N_f = 12$$

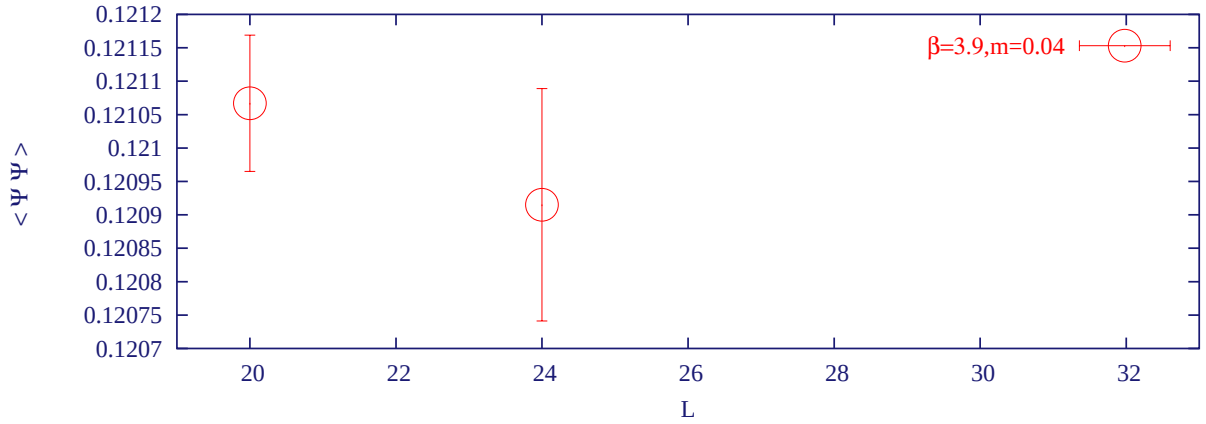
CHIRAL SYMMETRY





- Bulk transition
- Symmetry restored
- Focus on $g = 1.22, 1.24$ ($\beta = 3.9, 4.0$): Control of FV, thermalization.
- Use lattice QED as a paradigma for the symmetric phase


β=3.9, L =20
β=3.9, L=24
< ψ ψ >
m


β=3.9,m=0.04
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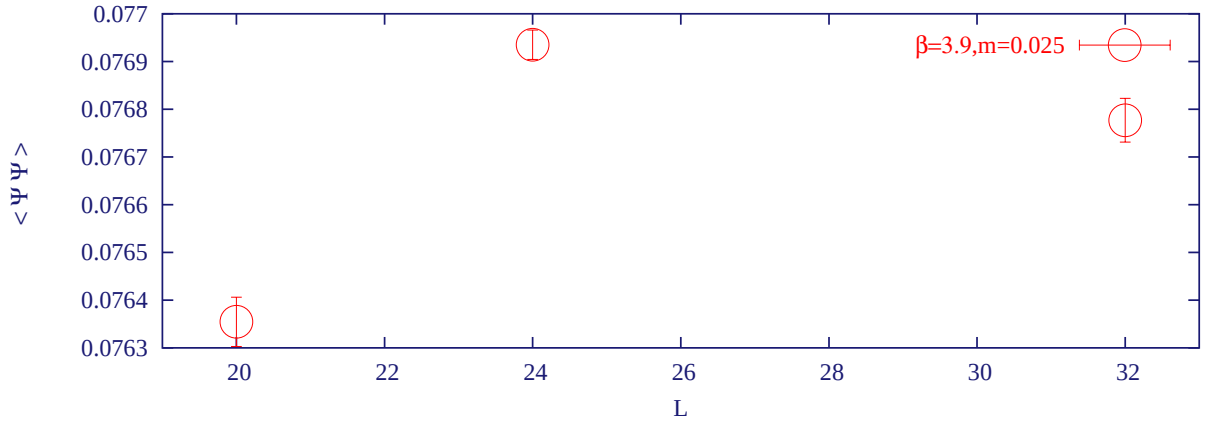
L


β=3.9,m=0.025
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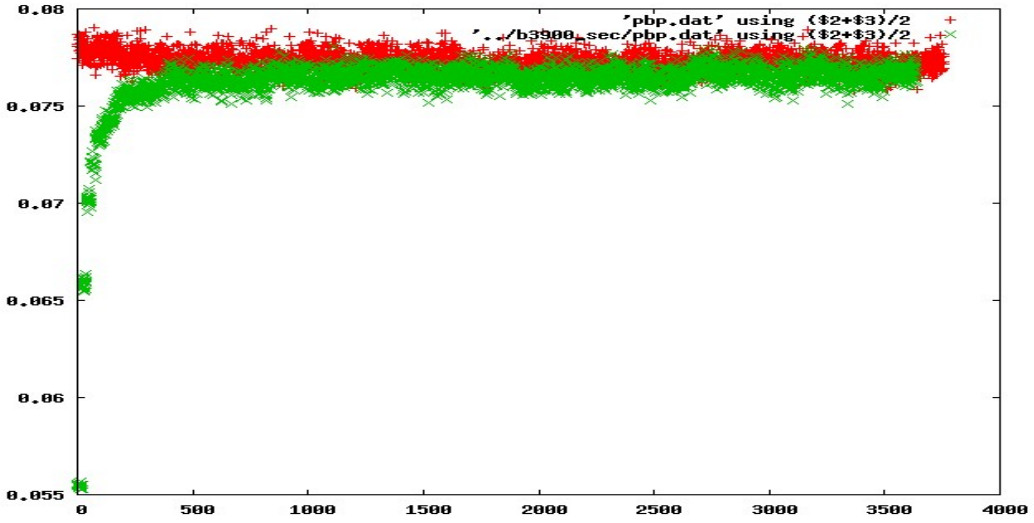
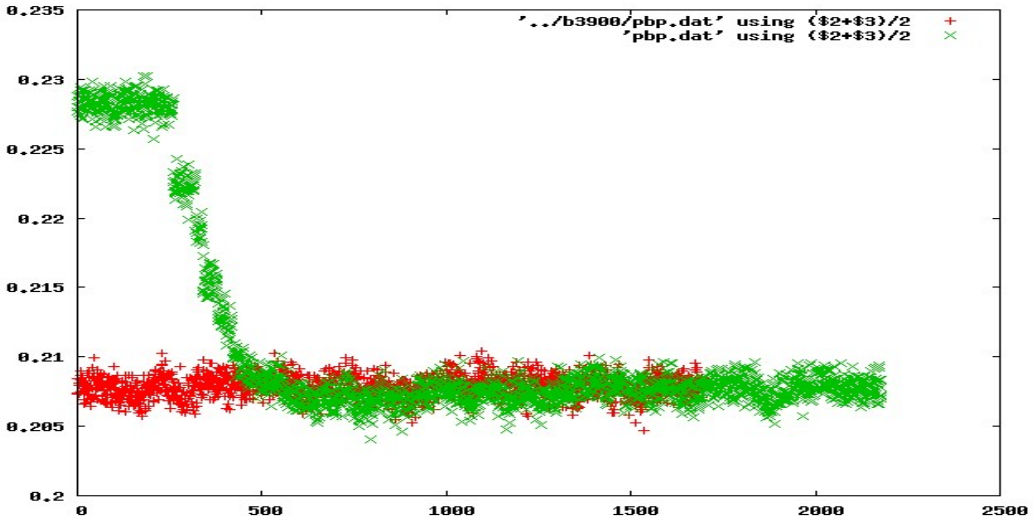
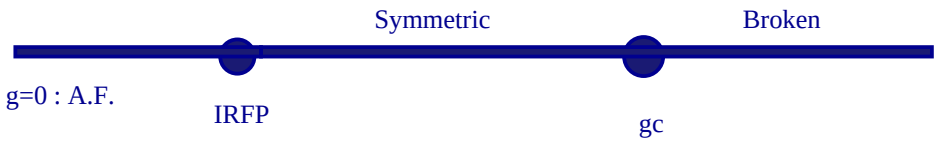
L



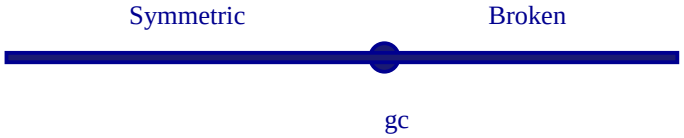
$\beta = 3.9, m = 0.025$



$\beta = 3.9, m = 0.07$

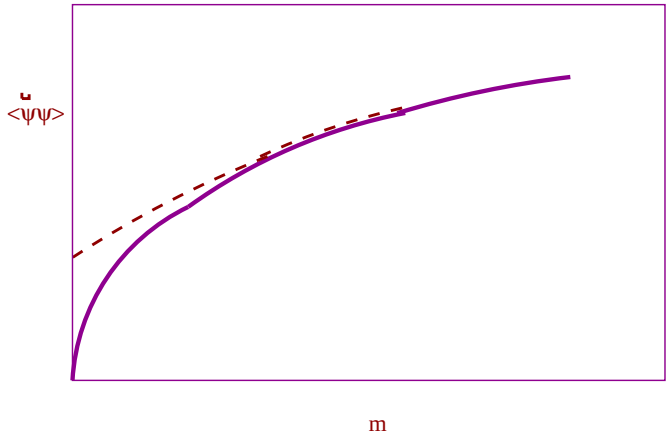


QCD Conformal

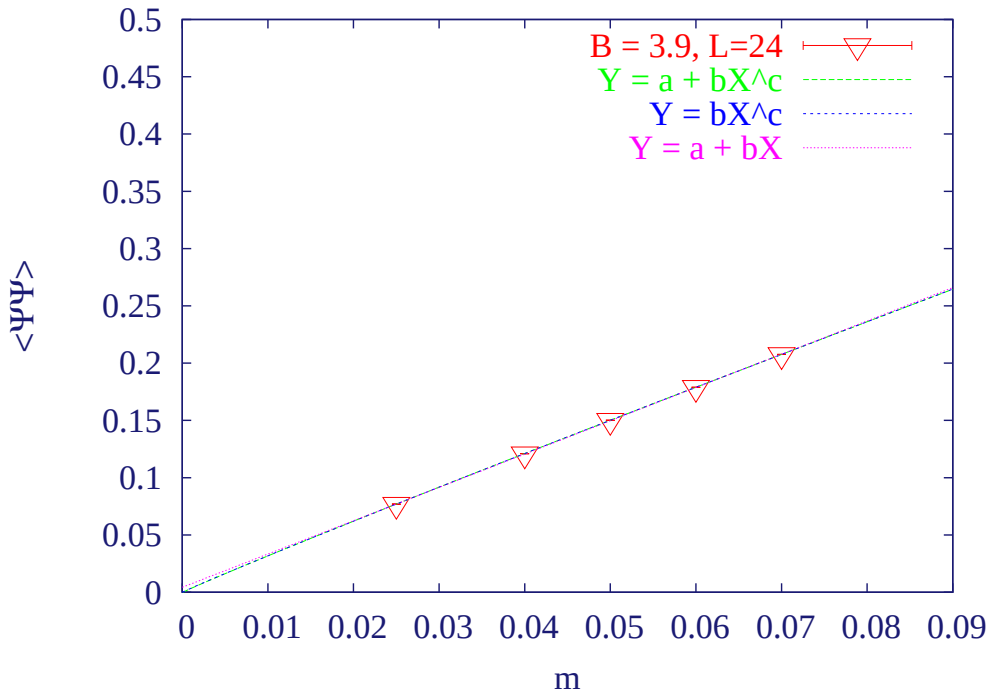


QED

- At the critical point g_c
  $\langle\bar{\psi}\psi\rangle = am^{1/\delta}$
- In the symmetric phase
  Conformality perturbatively broken by Coulomb forces:
  $\langle\bar{\psi}\psi\rangle = am^{d}$
- Only when conformal invariance is exact:
  $d = 1$.
- d measured in QED
  (**Kogut et al. 1985)**
  $1/\delta < d < 1$



- $\langle\bar{\psi}\psi\rangle = am^{d}$
  Symmetric Phase
- $\langle\bar{\psi}\psi\rangle = am + b$
  Broken Phase
  –Contrast χ^2 of different fits –

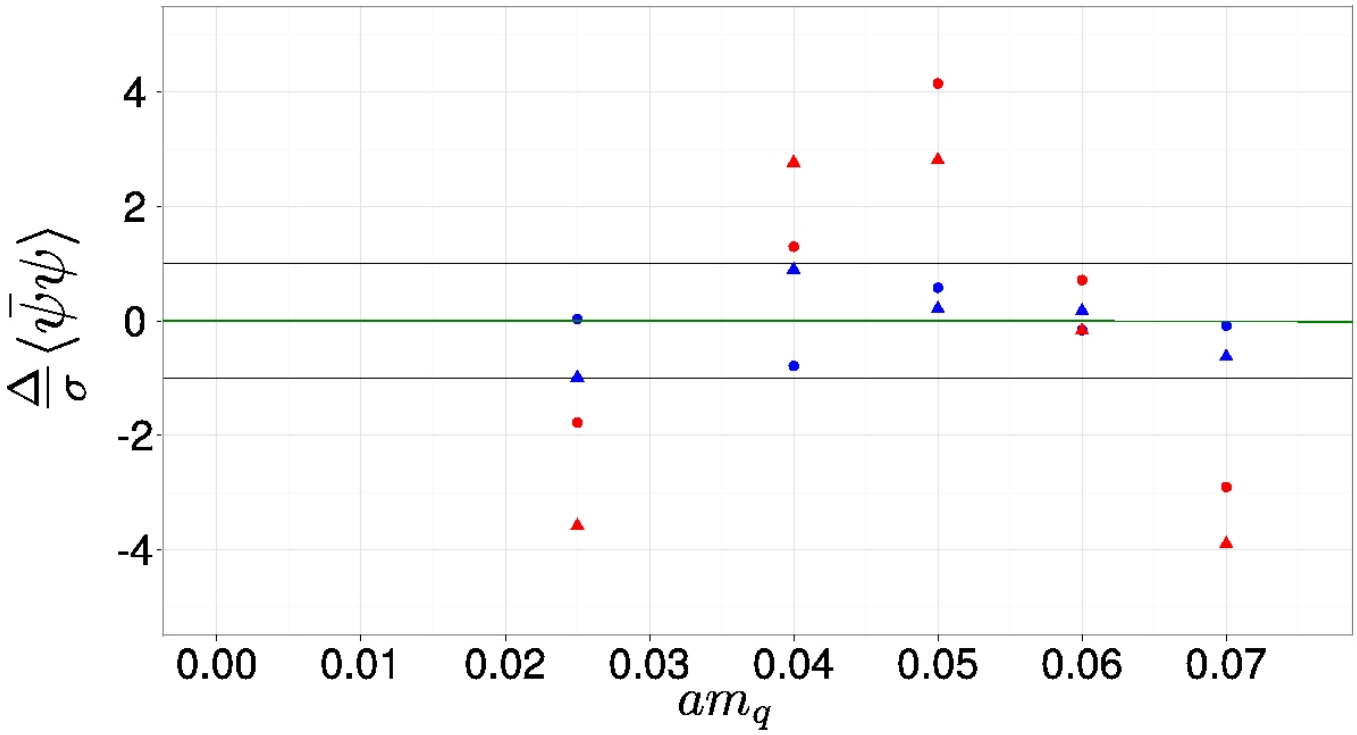


- $Y = a + bX^c$: Chiral Symmetry Broken if $a \neq 0$
  (χ^2/ndf) = 0.5, a = -0.0003(5) b = 2.68(2) c = 0.962(4)

- $Y = bX^c$: **Chiral Symmetry : Favored**
  (χ^2/ndf) = 0.4, b = 2.697(2) c = 0.9642(3)

- $Y = a + bX$: Chiral Symmetry Broken if $a \neq 0$
  (χ^2/ndf) = 3.9, a = 0.004(2) b = 2.907(5)

DATA FAVOR CHIRAL SYMMETRY



$\beta = 3.9$
$L = 20, 24$

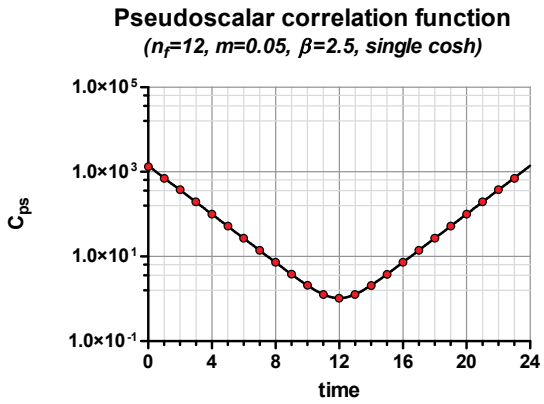
Blue Symbols : Chiral restoration : favored

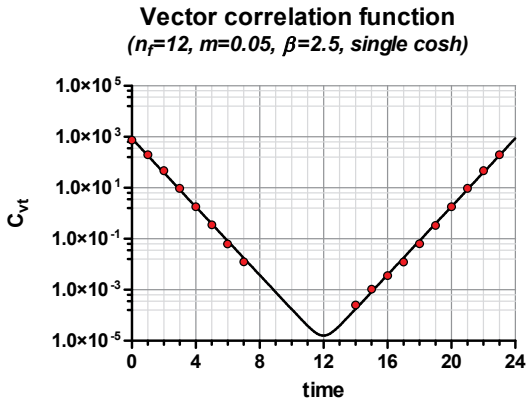
Red Symbols : Chiral breaking

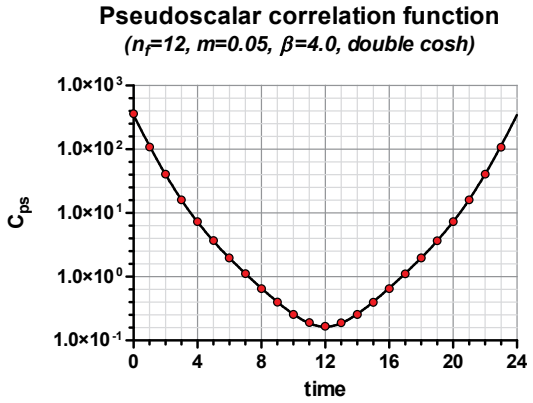
$\beta = 3.9$, L 20
Power law with an intercept a = -0.0039(6): (χ^2/ndf) = 0.60
Linear fit:$(\chi^2/ndf) = 4.4$.
$\beta = 3.9$, L 24
Pure power law: (χ^2/ndf) = 0.64 with exponent 0.9642(3)
Linear fit: (χ^2/ndf) = 3.9

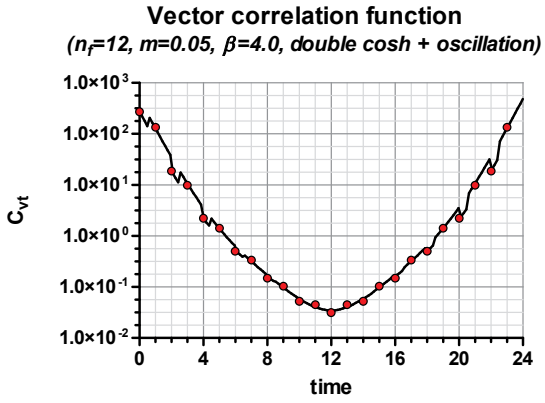
$\beta = 4.0$, L 20
Power law with an intercept a = -0.0011(9): (χ^2/ndf) = 0.78
Linear fit: (χ^2/ndf) = 3.1
$\beta = 4.0$, L 24
Pure power law: (χ^2/ndf) = 0.87 with an exponent of 0.965(1)
Linear fit: (χ^2/ndf) =3.8

SPECTRUM

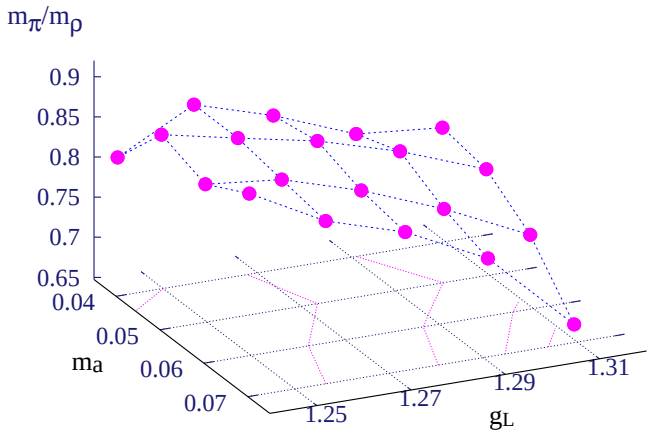

Pseudoscalar correlation function
(n_f=12, m=0.05, β=2.5, single cosh)
C_{ps}
time

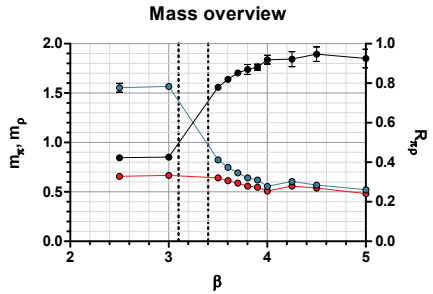

Vector correlation function
(n_f=12, m=0.05, β=2.5, single cosh)
C_{vt}
time


Pseudoscalar correlation function
(n_f=12, m=0.05, β=4.0, double cosh)
C_{ps}
time


Vector correlation function
(n_f=12, m=0.05, β=4.0, double cosh + oscillation)
C_{vt}
time

MASS RATIO : π/ρ



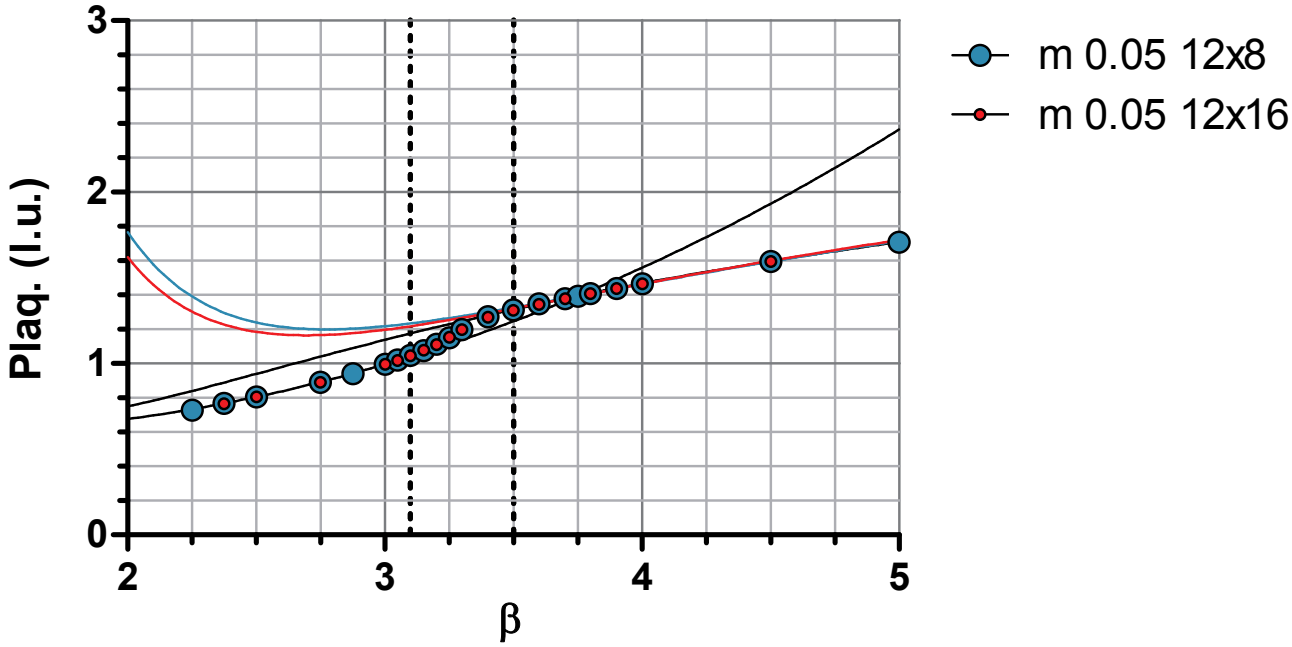


$m_\pi/m_\rho(m, g_L)$ = Constant
Defines isolines in the m, g_L plane

- Qualitative trend indicates that the bare mass should *increase* when g_L decreases to keep the m_ρ/m_π ratio constant
- Same trend should be observed in m_σ/m_π in the symmetric phase **Kogut et al. 1985–**
- The above points suggest that the lattice spacing increases with g_L
- This is the behaviour expected of a one parameter β function with a postive sign, again consistent with being in a QED phase.
- Same trend observed in QCD with Nf=16 **Damgaard et al. 1996**

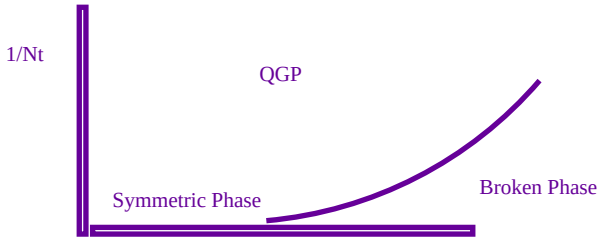
APPROACHING $g = 0$: NO SIGN OF FURTHER PHASE TRANSITIONS

Perturbative running of plaquette: $N_f = 12$



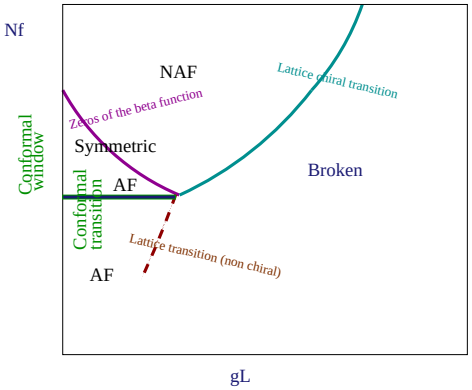
$N_f = 8$ and non-zero temperature

QGP and T=0 Symmetric Phase



In the conformal window

In the broken phase (ordinary QCI



1/Nt = Tphys * a(g^2)

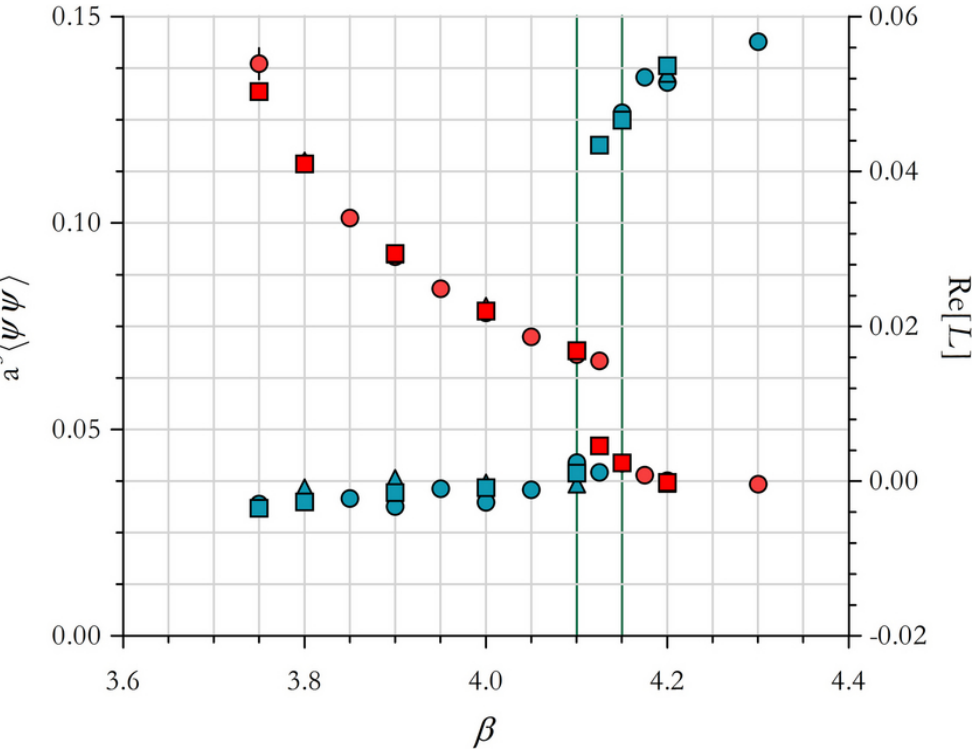
High T always restores chiral symmetry at $g = g_T$

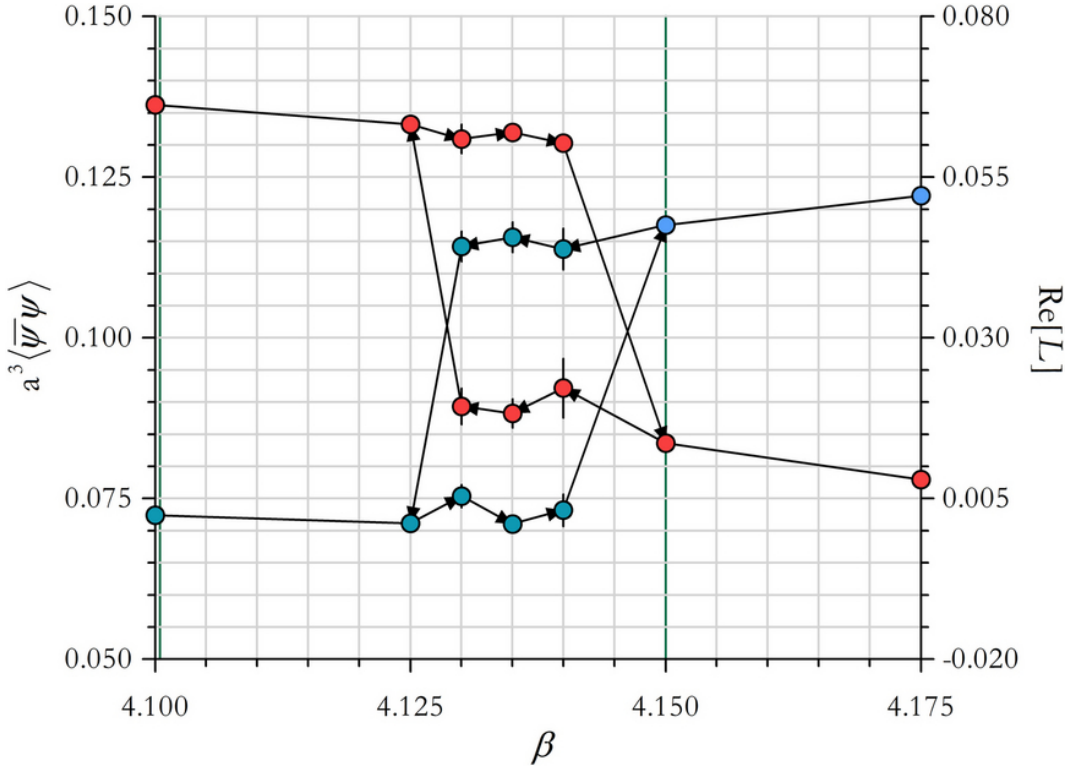
$\lim_{N_t \to \infty} g_T^2 = g_c^2$ in the symmetric phase

$\lim_{N_t \to \infty} g_T^2 = 0$ according to asymptotic scaling in the broken phase

Conformal phase = limit $T \to 0$ of QGP Phase

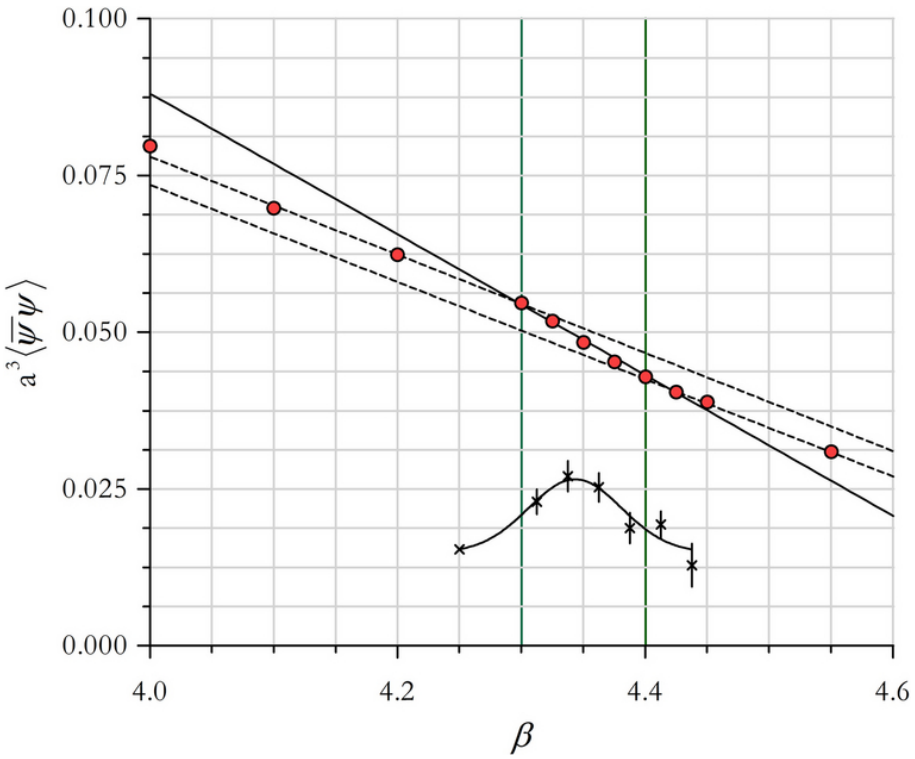
$N_t = 6$





N_s: 12 (◯), 20 (△), 24 ()

$N_t = 12$



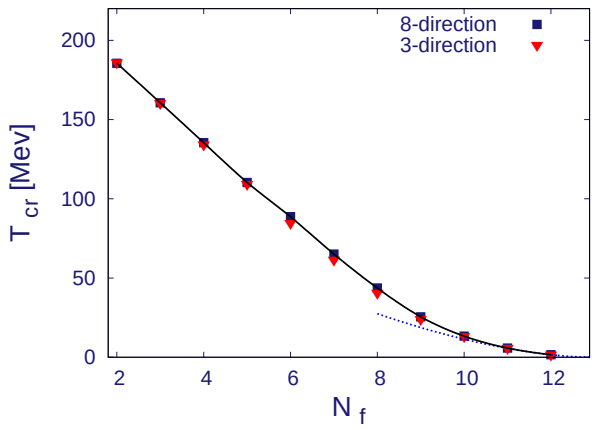
Thermal transition for
$N_f = 8$

$$T_c = \frac{1}{a(\beta_c) N_t}$$

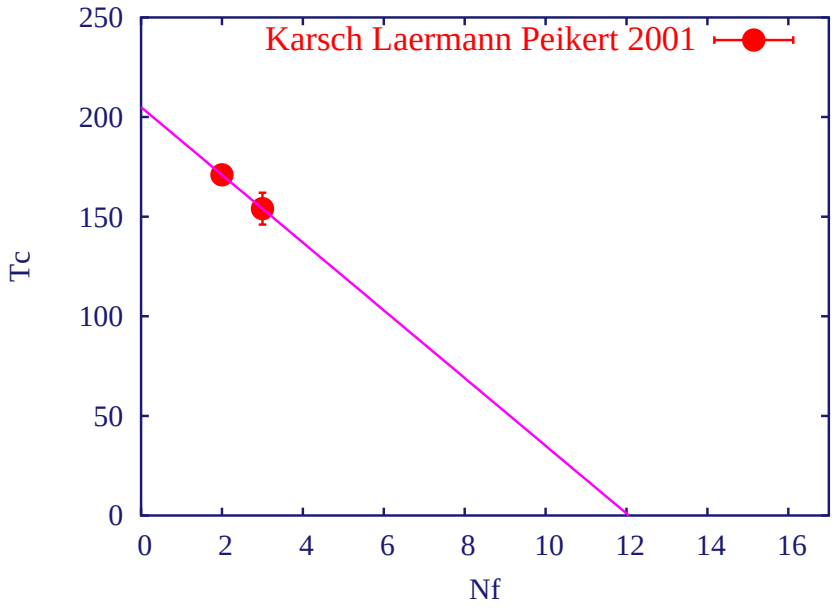
Satisfies asymptotic scaling within 2 %

$$\frac{6}{12} = \frac{a(\beta_c, N_t = 12)}{a(\beta_c, N_t = 6)}$$

PHASE DIAGRAM OF QCD IN THE T, N_f PLANE



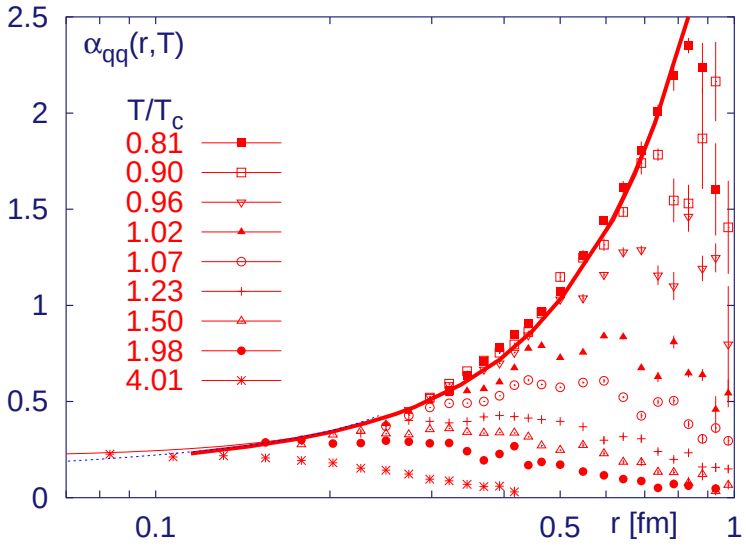
Braun, Gies 2007



$N_f = 8$ new point on the critical line

$N_f = 12$, if in the broken phase, might well have an extremely low critical temperature. This will make very difficult to distinguish a conformal phase from a quark gluon plasma phase.

RUNNING IN THE COLD - WALKING IN THE HEAT.
The running coupling from *quenched* QCD.



Kaczmarek e Zantow 2005

SUMMARY

- $N_f = 8$ in the broken phase
- $N_f = 12$
  - Strong indications of chiral symmetry restoration.
  - Chiral symmetry seems to persist till $g_L = 0$: No sign of further phase transitions.
  - Consistent with the realization of conformal scenario
  - **However : issue not settled yet. Many talks addressing this.**

$N_f = 12$, if in the broken phase, might well have an extremely low critical temperature. This most likely makes the quark gluon plasma phase very similar to a conformal phase.

N_f^c = 12 (3) World Average.

How crucial it is to push the error to zero?