QCD with many flavors at zero and non-zero temperature

Maria Paola Lombardo

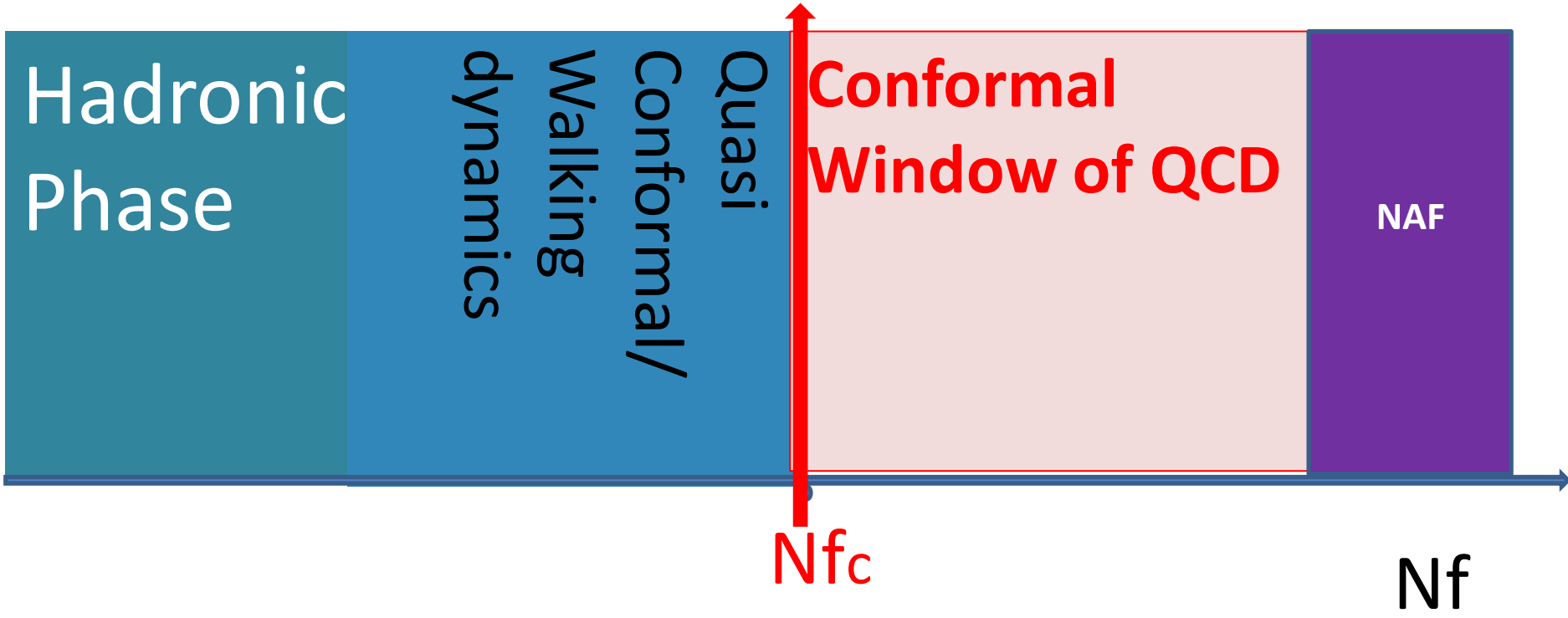
Albert Deuzeman, MPL , Kohtaroh Miura , Tiago Nunes da Silva, Elisabetta Pallante

New Frontiers of Lattice Field Theories

GGI Firenze

17 September 2012

QCD with many flavors : Sketchy view of the phase diagram



(ideal) Outline

- Nf=0
- Nf=1
- Nf=2
- Nf=3
- Nf=4
- Nf=5
- Nf=6
- Nf=7
- Nf=8
- Nf=9
- Nf=10
- Nf=11
- Nf=12
- Nf=13
- Nf=14
- Nf=15
- Nf=16
- Summary

Outline

- **Nf=0**
- Nf=2
- Nf=3
- **Nf=4**
- Nf=5

Introduction

- **Nf=6**
- Nf=7
- **Nf=8**
- Nf=9

Near Conformal: Continuum and Lattice

- Nf=13
- Nf=14
- Nf=15
- Nf=16

Conformal

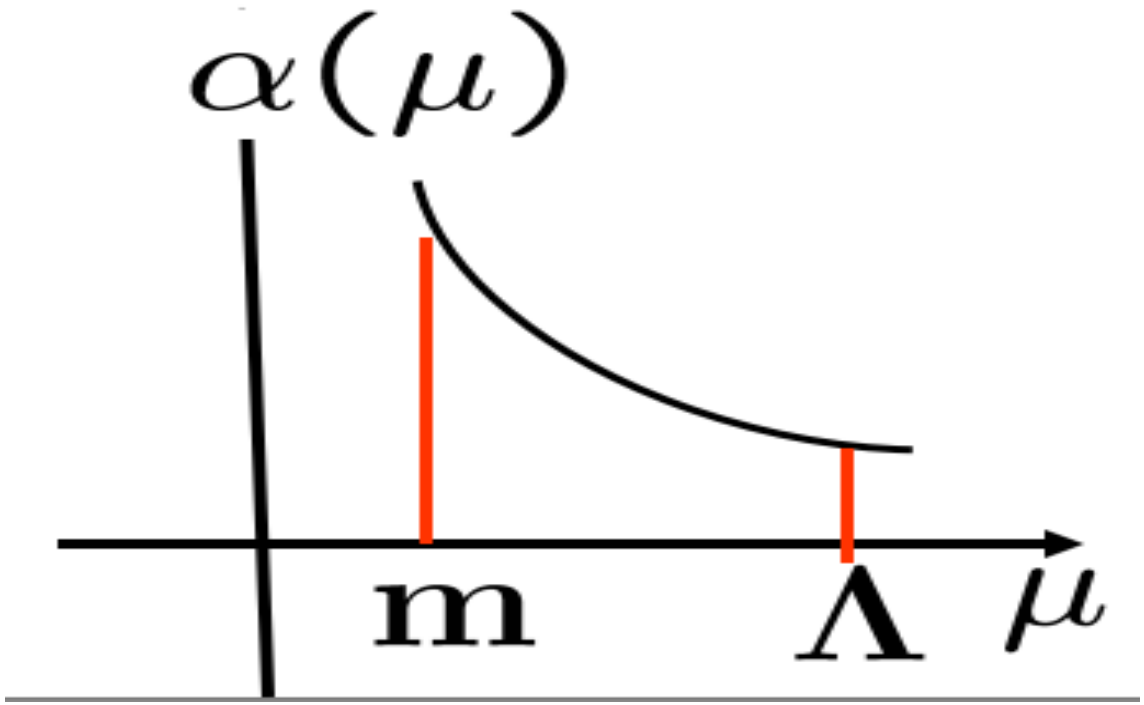
Summary

$Nf_c \approx 12$

Near Conformal: Continuum and Lattice

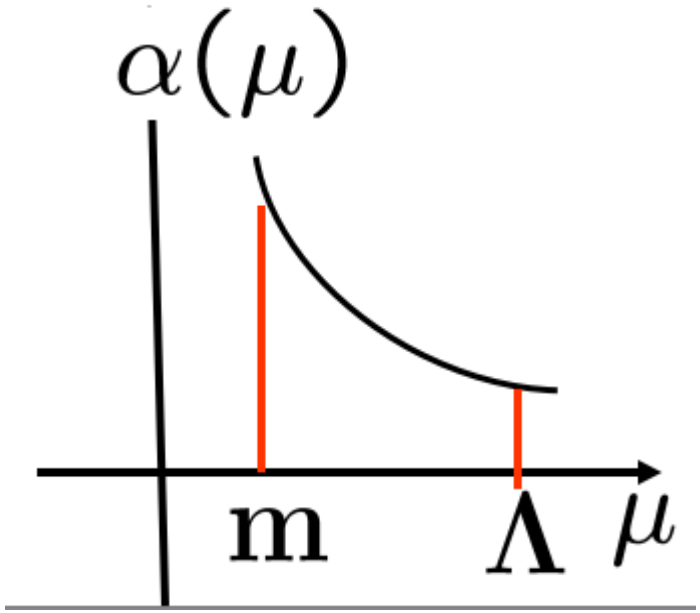
This talk's main theme: precursors effects of conformality when approaching Nfc from the QCD side

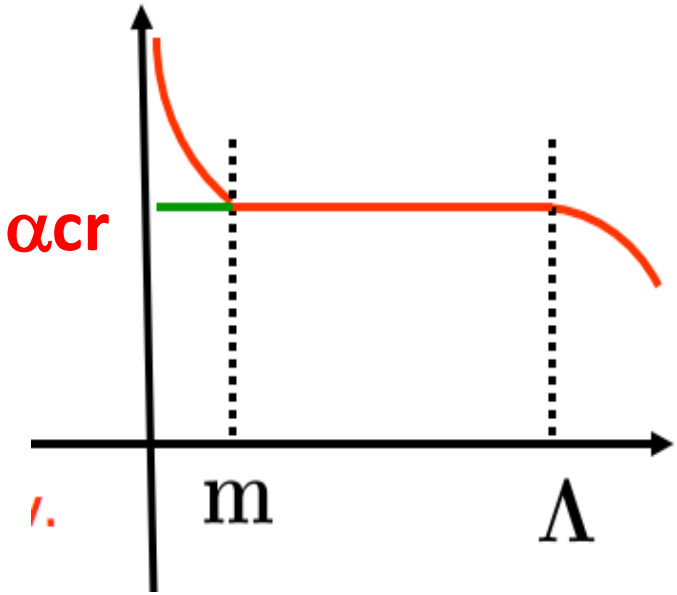
QCD-like : running coupling



Running vs Walking :

Both compatible with IR slavery and UV freedom





Running :

Λ *sets the scale*

Walking :

***Separation of Scales*:**

Interesting for Phenomenology

The discovery of the conformal window of QCD

Miransky-Yamawaki, 1997; Appelquist et al. 1997

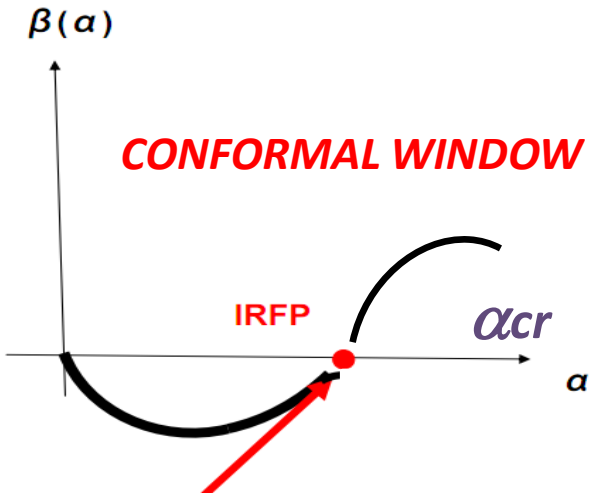
•*For* $Nf > 8$ *the perturbative* β *function of QCD develops a second 0 : the Banks-Zacs* **IRFP** .

•*Then the coupling runs to* **IRFP**

•*Chiral Symmetry Breaking requires* $\alpha > \alpha cr$:

• *1)* **IRFP** $< \alpha cr$ →

CONFORMAL WINDOW

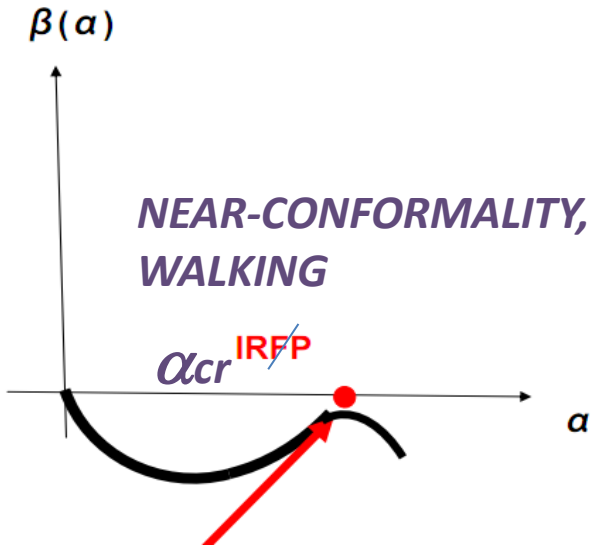


2) **IRFP** $> \alpha cr$ →

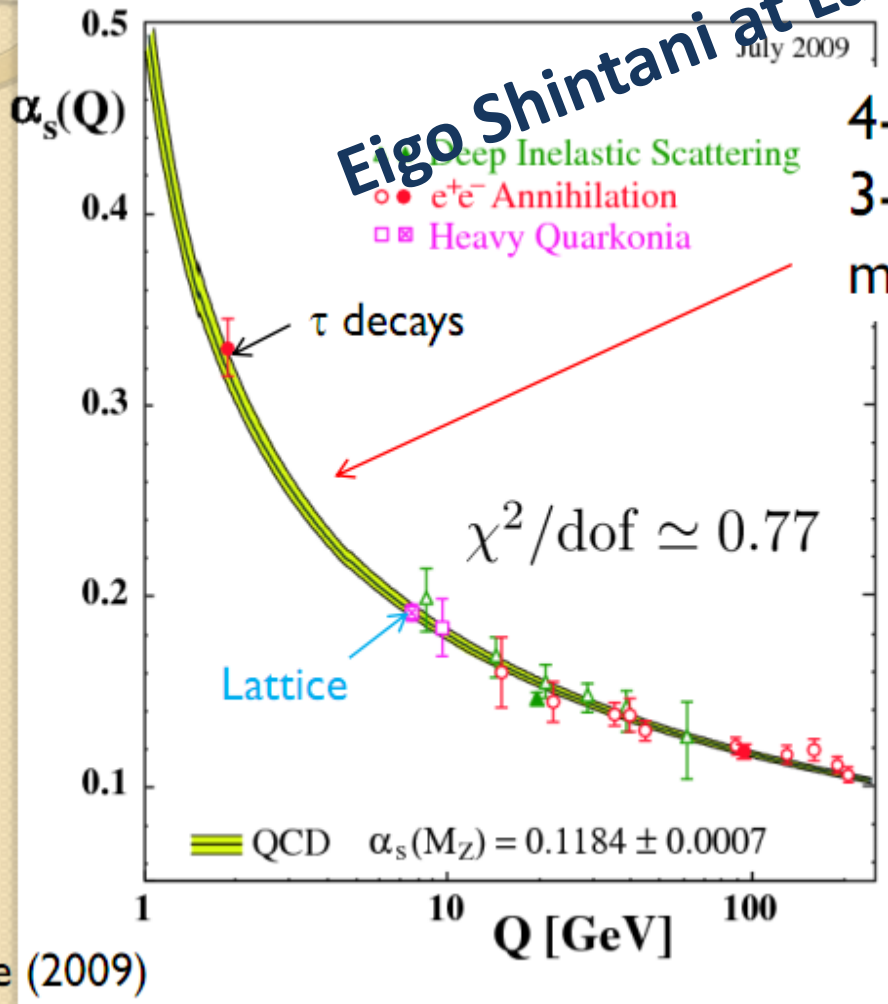
IRFP disappears

QCD-like, but:

NEAR-CONFORMALITY, WALKING



Eigo Shintani at Lattice 2011



Bethke (2009)

4-loop (N^4 LO) pQCD and
3-loop matching formula at
m_c = 1.5 GeV and m_b = 4.7 GeV

Running established

Running established up to 5 Flavors

Can we establish walking as well?

Can we establish walking as well?
(if yes, it has to be for Nf > 5)

Near-Conformal behaviour
On the QCD-side can be seen in:

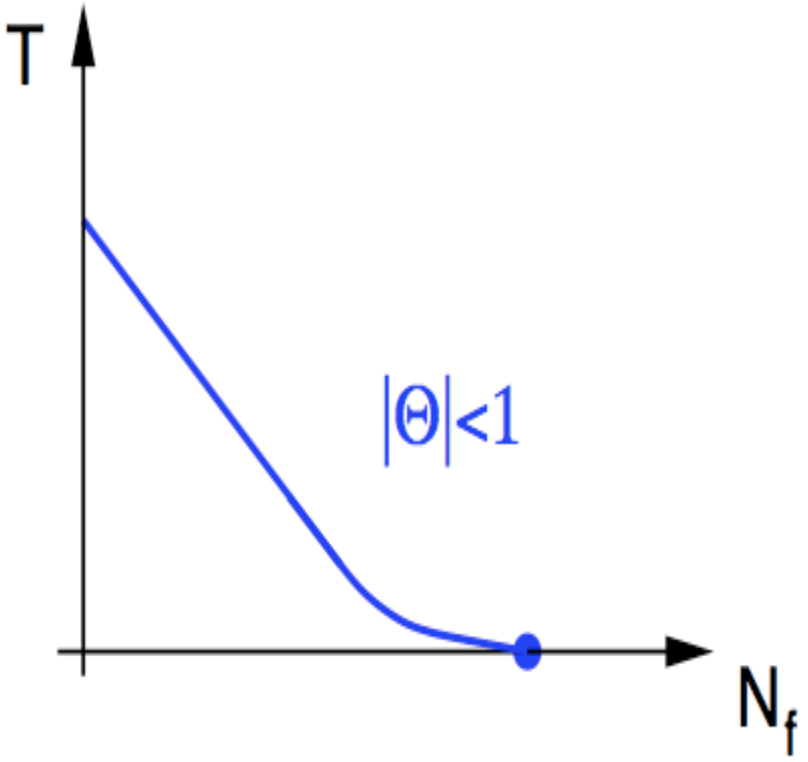
Different scales Λ_{UV} and Λ_{IR}

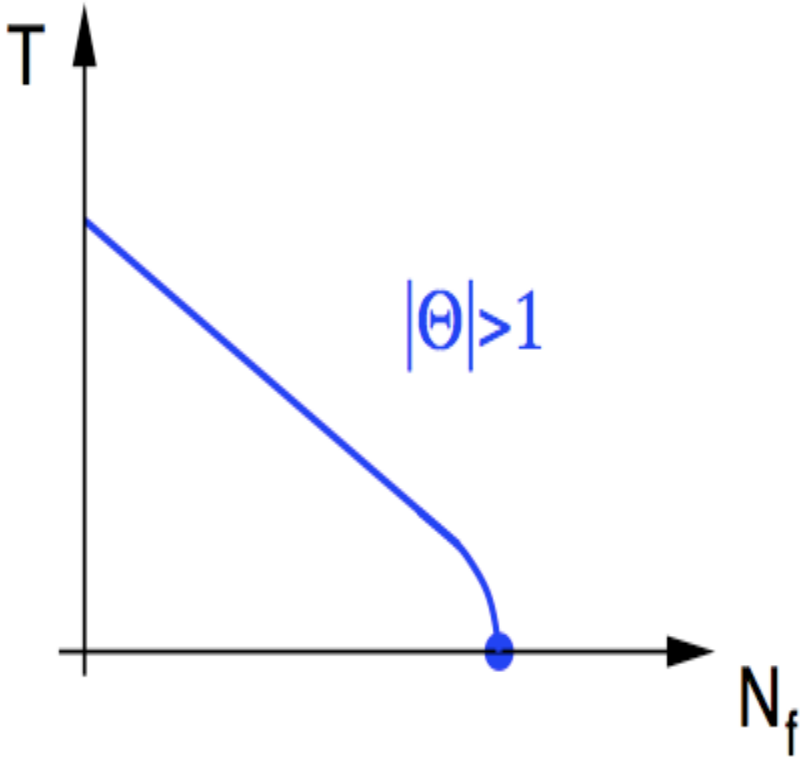
Critical behaviour Nf ⟶ Nfc

$$m\ (N_f) = K|N_f - N_f^c|^{-1/\theta}\ .$$

Thermal transition and near-conformal dynamics

J. Braun , H. Gies 06 08 09

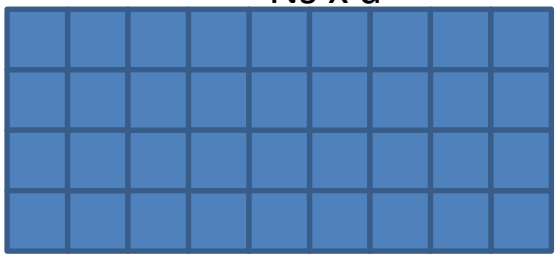




Towards Conformality: Continuum (from the lattice)

Ns x a

Nt x a



From the Lattice..

$$T \equiv \frac{1}{a(\beta_L) \cdot N_t} ,$$

..to the continuum

Via old fashioned asymptotic scaling

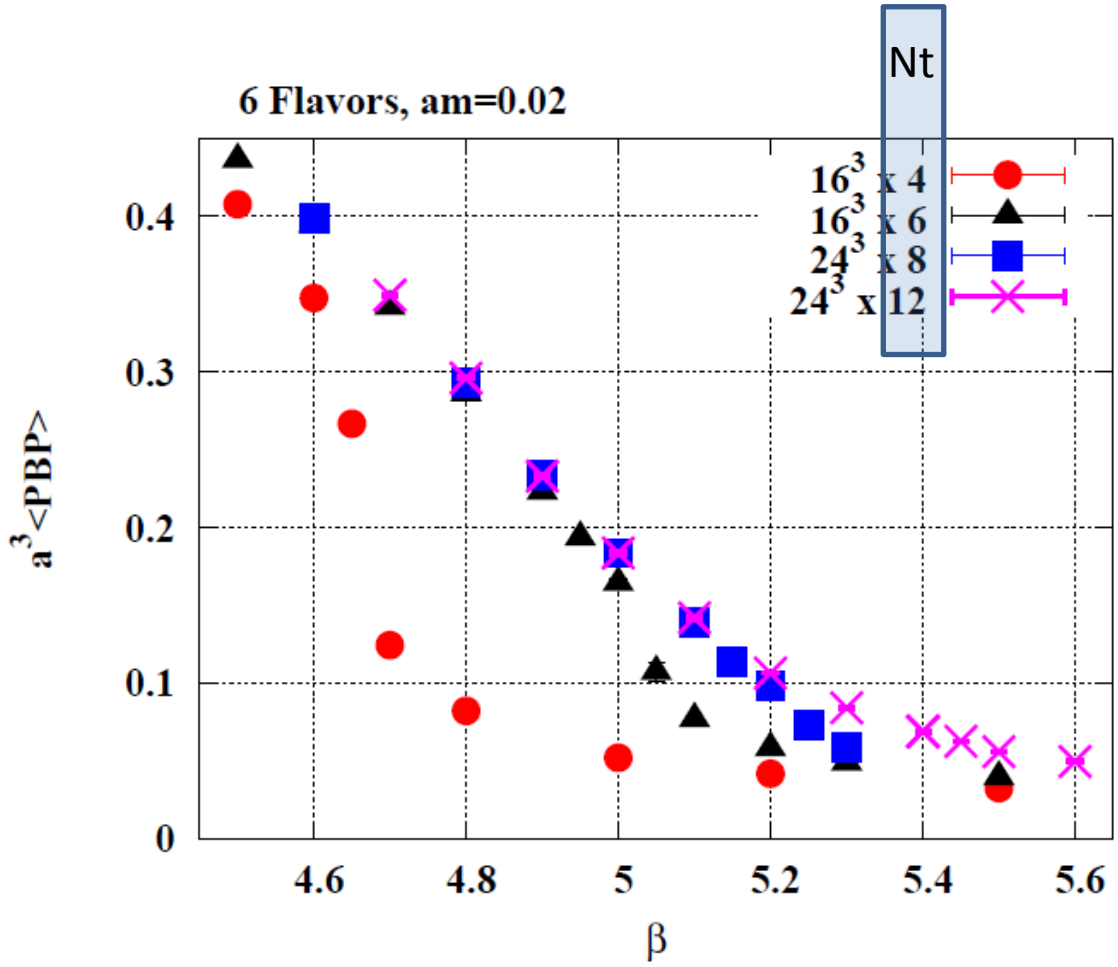
$$\Lambda_L \, a(\beta_L) = \left(\frac{2 N_c b_0}{\beta_L} \right)^{-b_1/(2b_0^2)} \exp\left[\frac{-\beta_L}{4 N_c b_0} \right] .$$

$$\frac{1}{N_t} = \frac{T_c}{\Lambda_L} \times \left(\Lambda_L \, a(\beta_L^c) \right) .$$

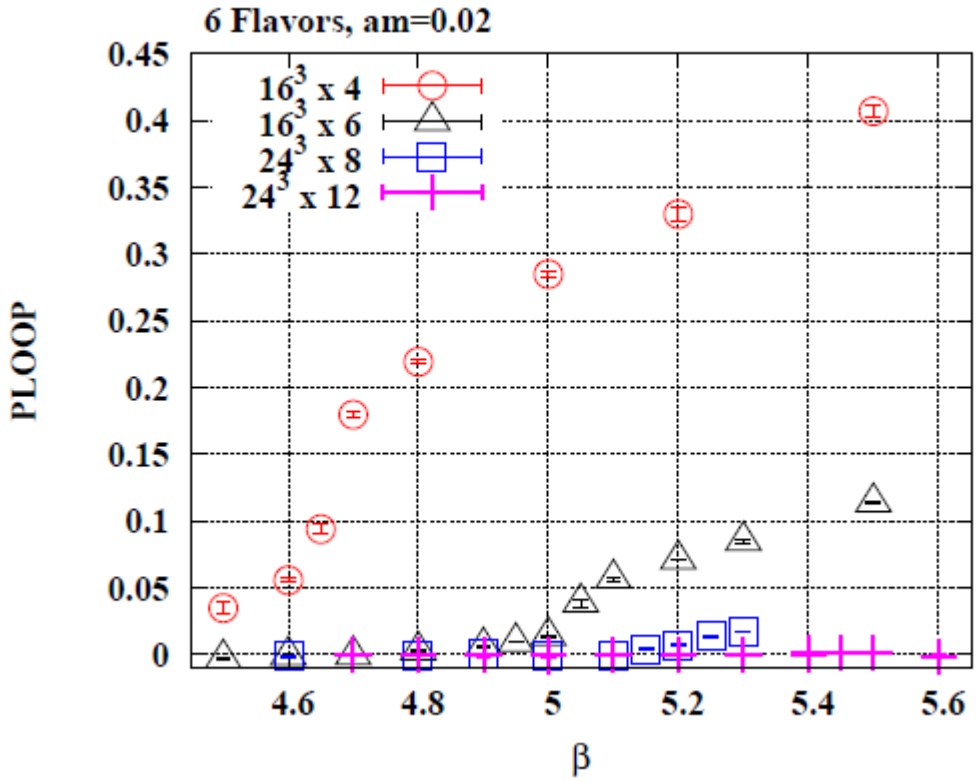
Must be approx. constant for several Nt

(Old fashioned asymptotic scaling)

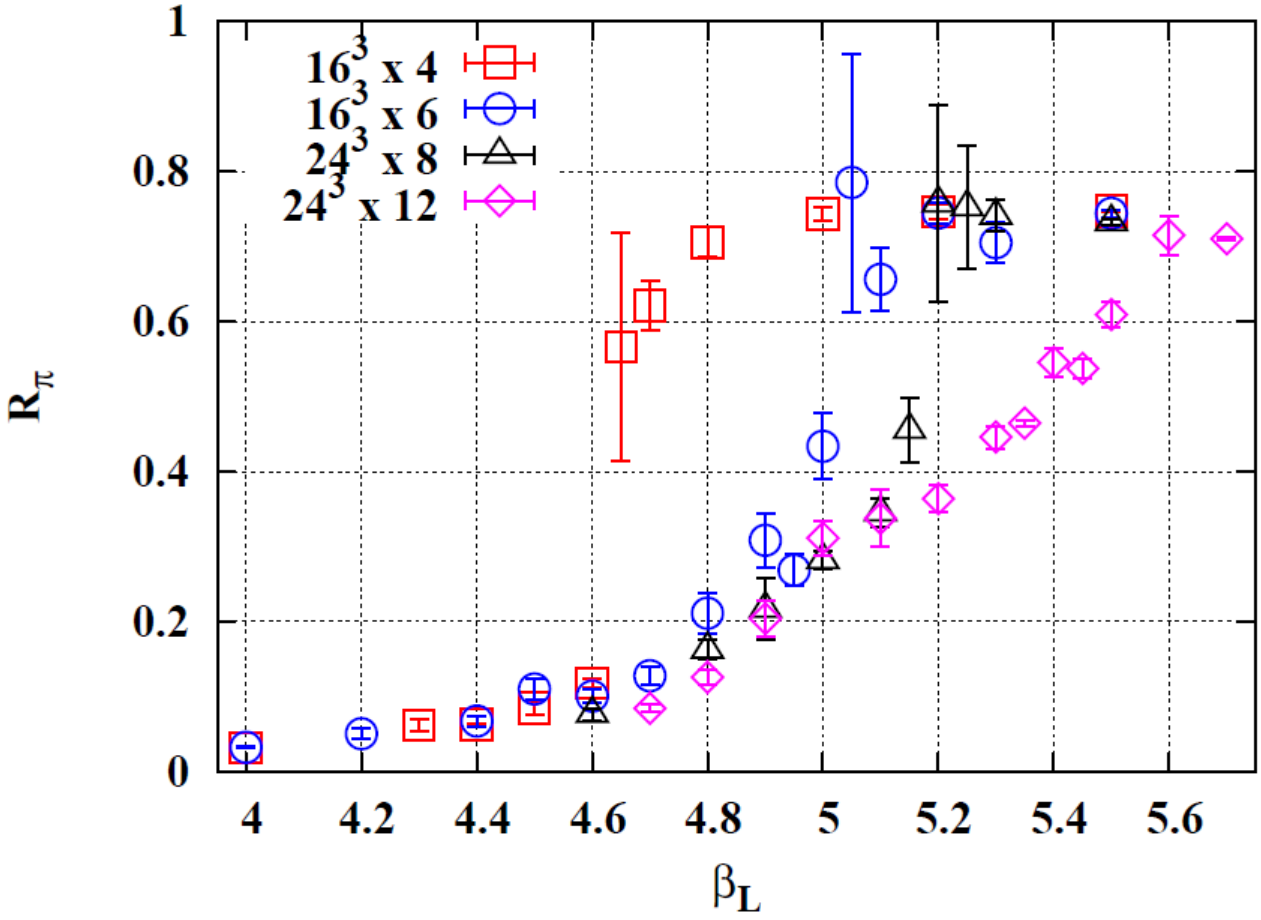
Nf = 6 Chiral crossover of order parameter



Nf=6 , Polyakov loop



Nf=6 : Chiral crossover of the chiral cumulant Rπ



Summary of results for βc (updated at xQCD2012)

Table: $N_f = 0,\ 4,\ 6$: Miura-Lombardo-Pallante ('12), $N_f = 8$: Deuzeman-Lombardo-Pallante ('08)

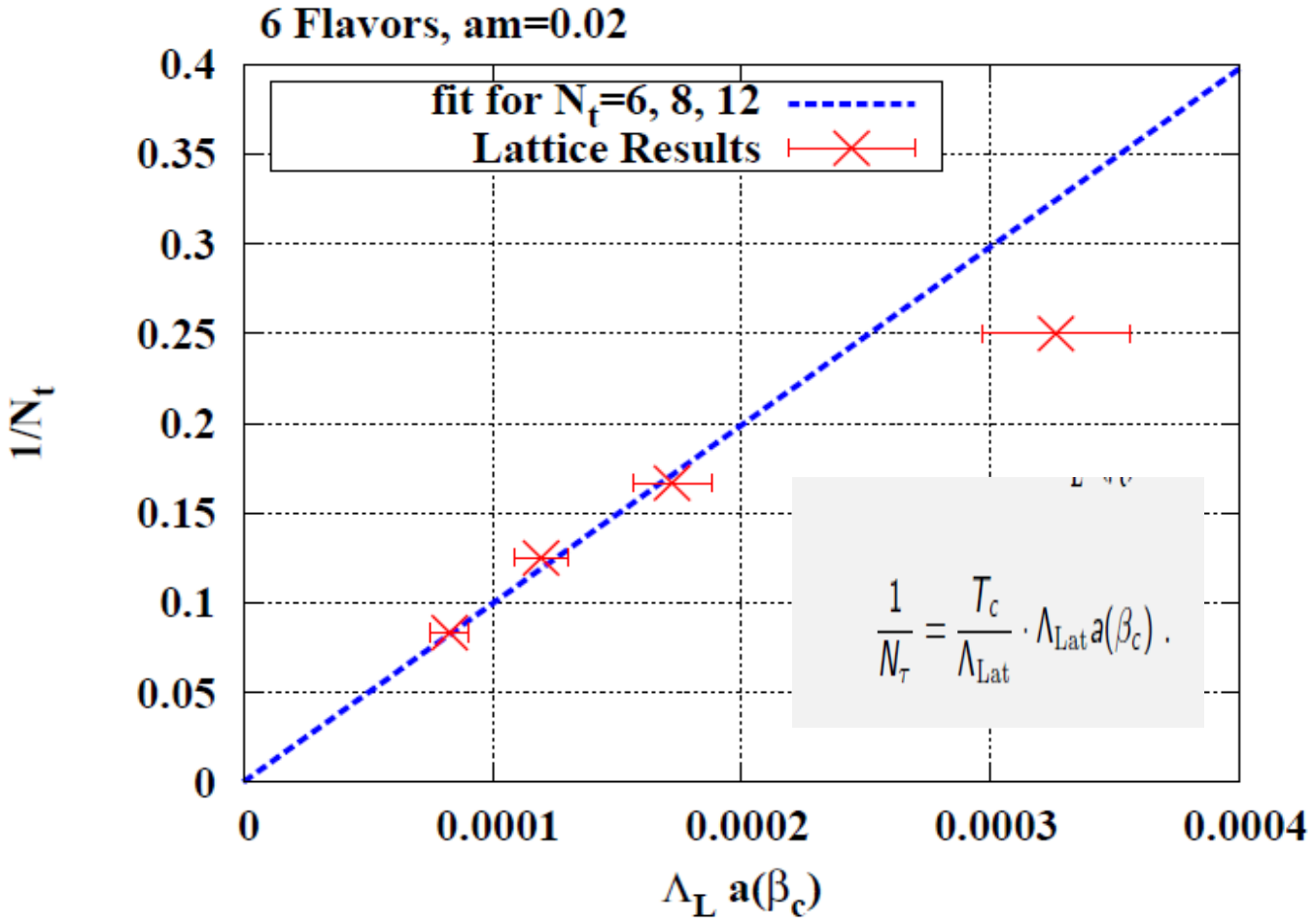
$N_f \backslash N_t$	4	6	8	12
0	7.35 ± 0.1	7.88 ± 0.05	8.20 ± 0.1	-
4	-	5.89 ± 0.05	-	
6	4.65 ± 0.05	5.05 ± 0.05	5.2 ± 0.05	5.55 ± 0.1
8	-	4.1125 ± 0.0125	-	4.34 ± 0.04

- The Monte-Carlo simulations have been performed by using the same lattice action (one-loop Symanzik tad-pole improved AskTad action) up to

$$\frac{1}{N_t} = \frac{T_c}{\Lambda_{\rm L}} \times \left(\Lambda_{\rm L}\ a(\beta_{\rm L}^{\rm c})\right).$$

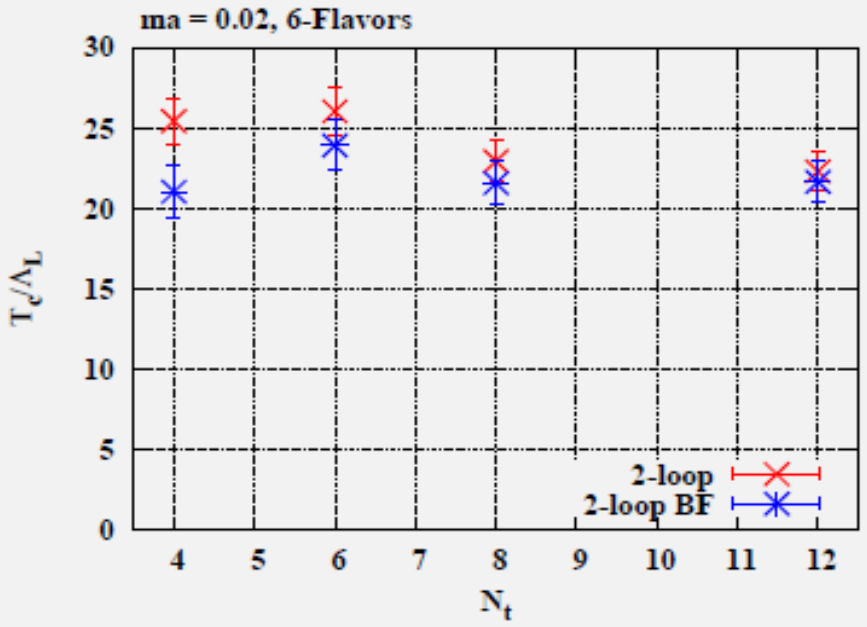
Must be Nt independent

Nt-(quasi) independence of T_c/Λ_{Lat} for Nf = 6



Asymptotic Scaling of T_c/Λ_L

Slide from
K. Miura
xQCD2012

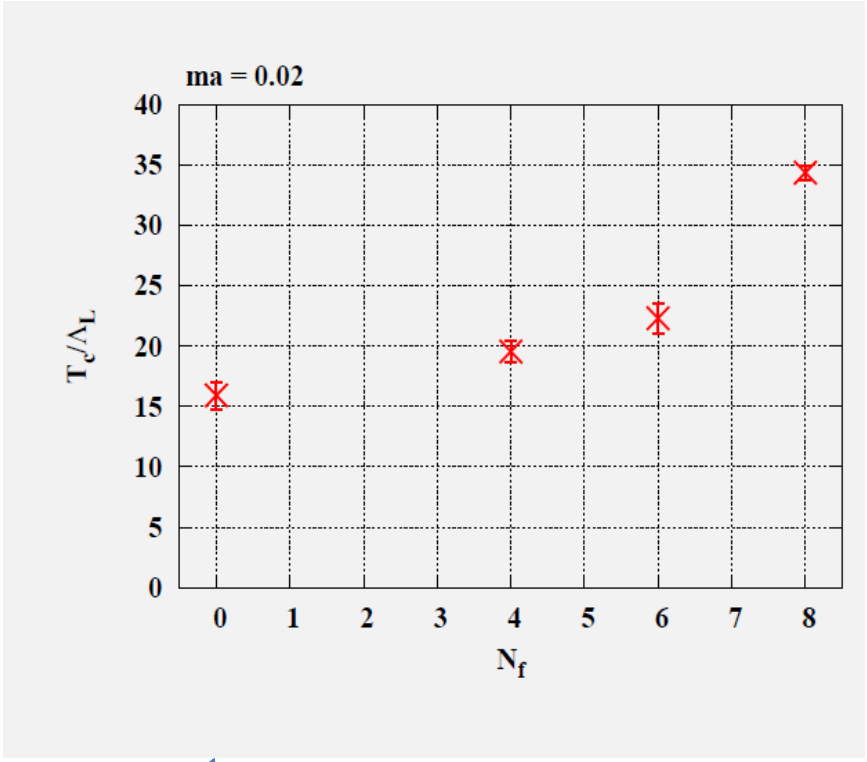


The critical couplings $\beta_L{}^c$ has been obtained,

- near to the continuum limit,
- with a controlable scaling violation
  with the use of Bielefeld improvement (Cheng et.al. ('08)).

Tc/Λ as a function of Nf

Tc/Λ

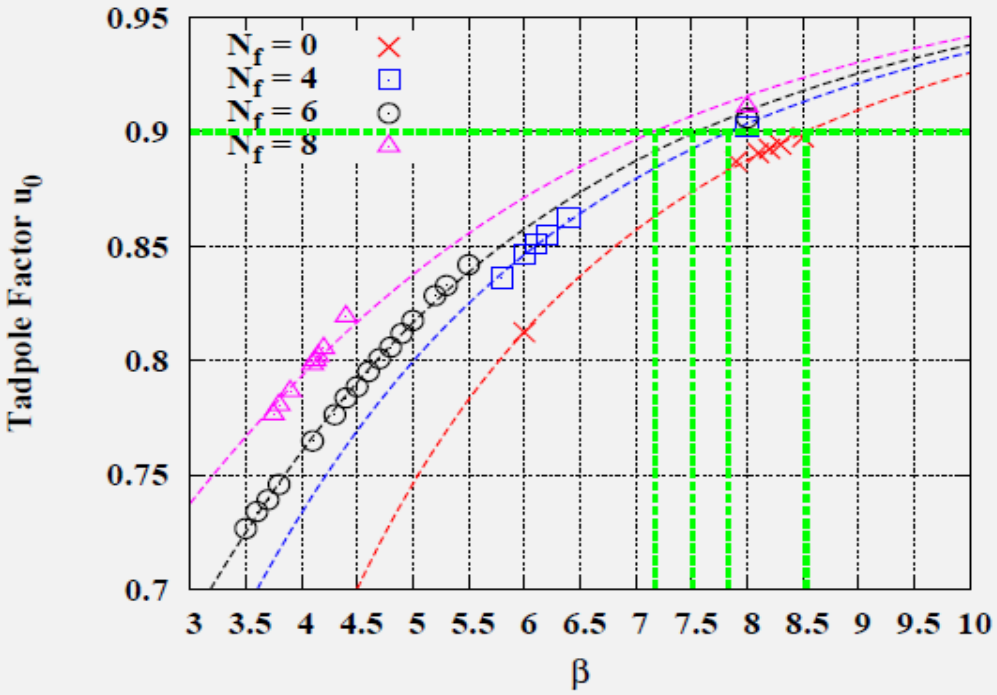


Scale separation

Nf

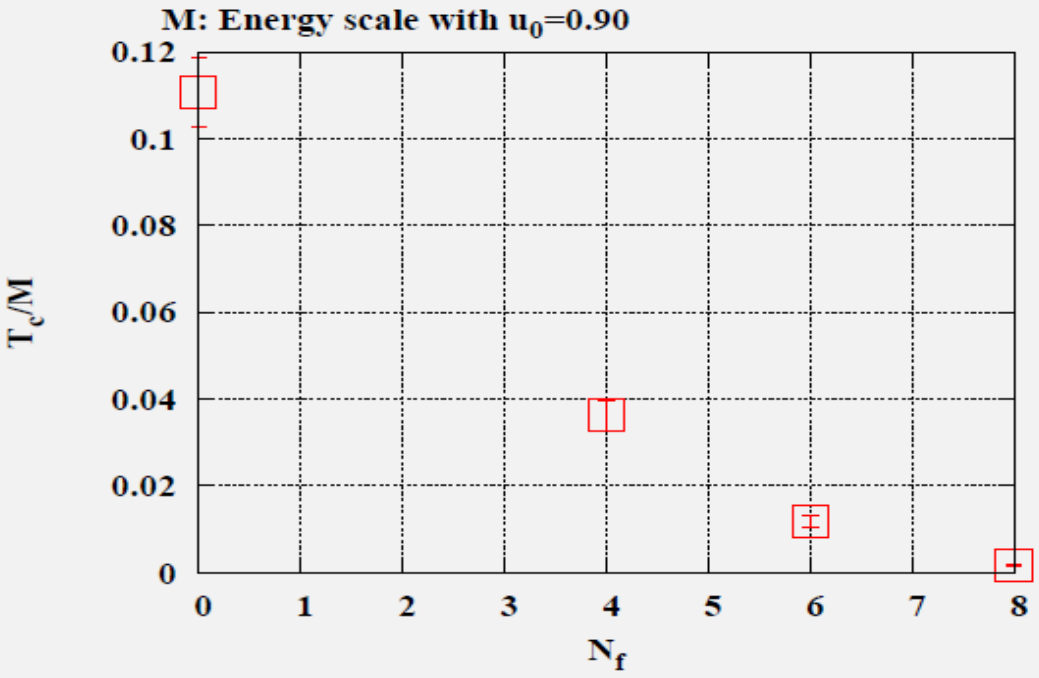
Conventional running

Fixing an UV scale



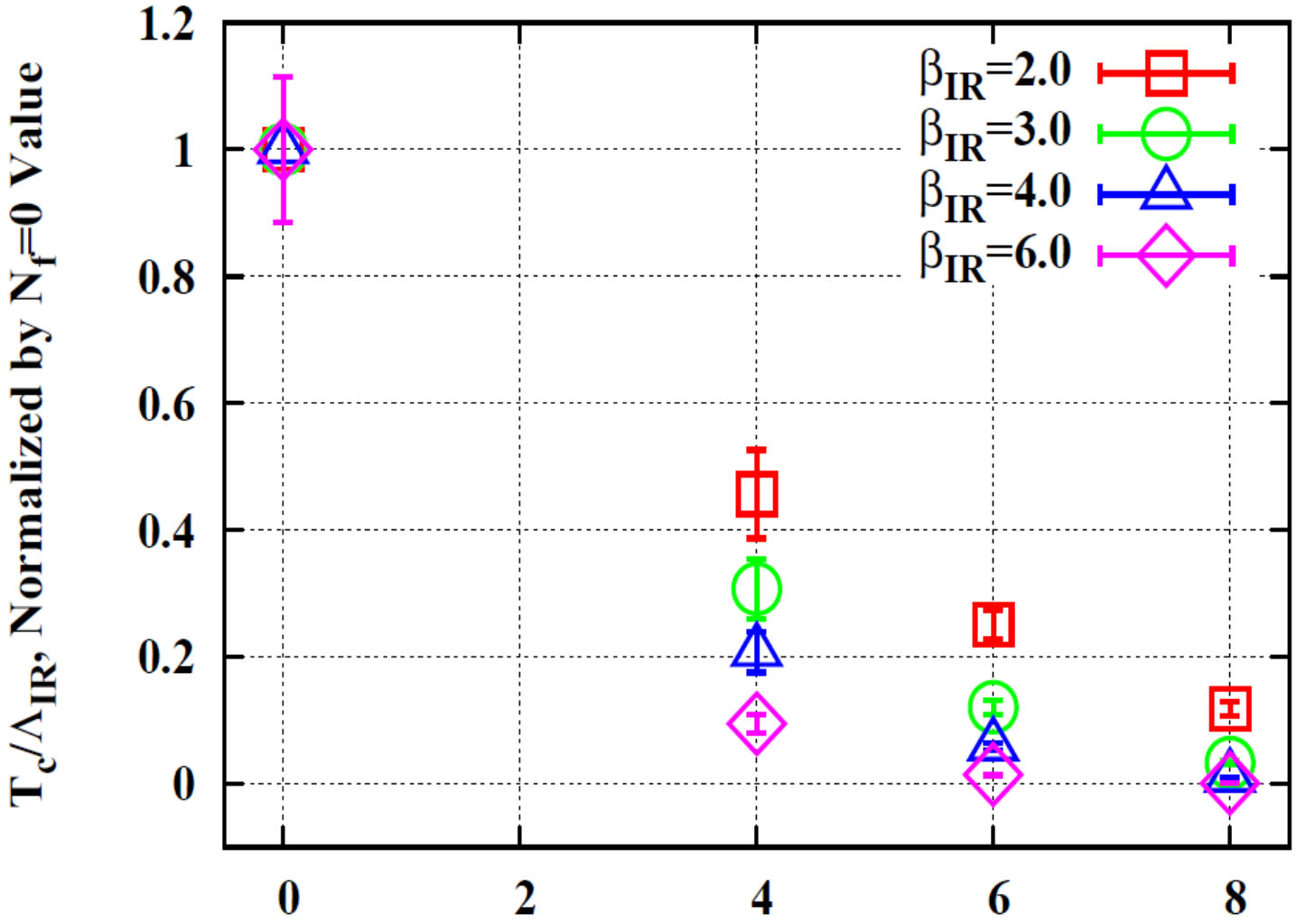
- We have measured the tadpole factosr $u_0 = \langle \Box \rangle^{1/4}$ at $T = 0$.
- We use the couplings obtained by the constant u_0 line to define a UV reference scale M.

T_c/M_{UV}

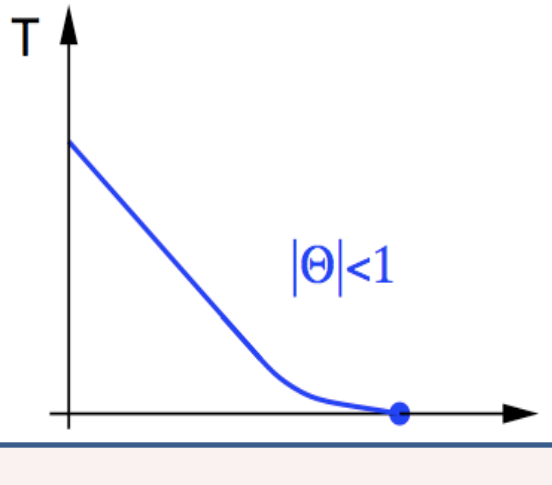


$$\frac{T_c}{M} = \frac{1}{N_t} \exp\left[\int_{g_{\rm ref}}^{g_c} \frac{dg}{B(g)}\right] .$$

Trading Λ_{LAT} for Λ_{IR} stable

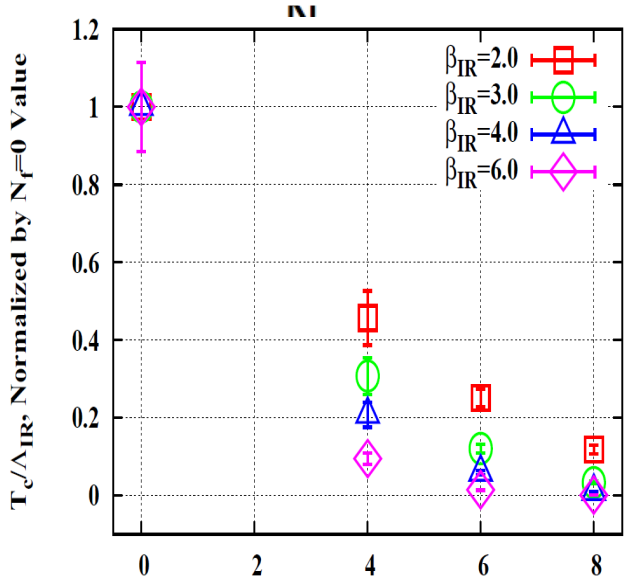


$$T_c(N_f) = K|N_f - N_f^c|^{-1/\theta} \quad . \quad 1.1 < 1/|\theta| < 2.5,$$



$$N_f^c = 9(1) \text{ for } \beta_L^{\text{ref}} = 4.0$$

$$N_f^c = 11(2) \text{ for } \beta_L^{\text{ref}} = 2.$$

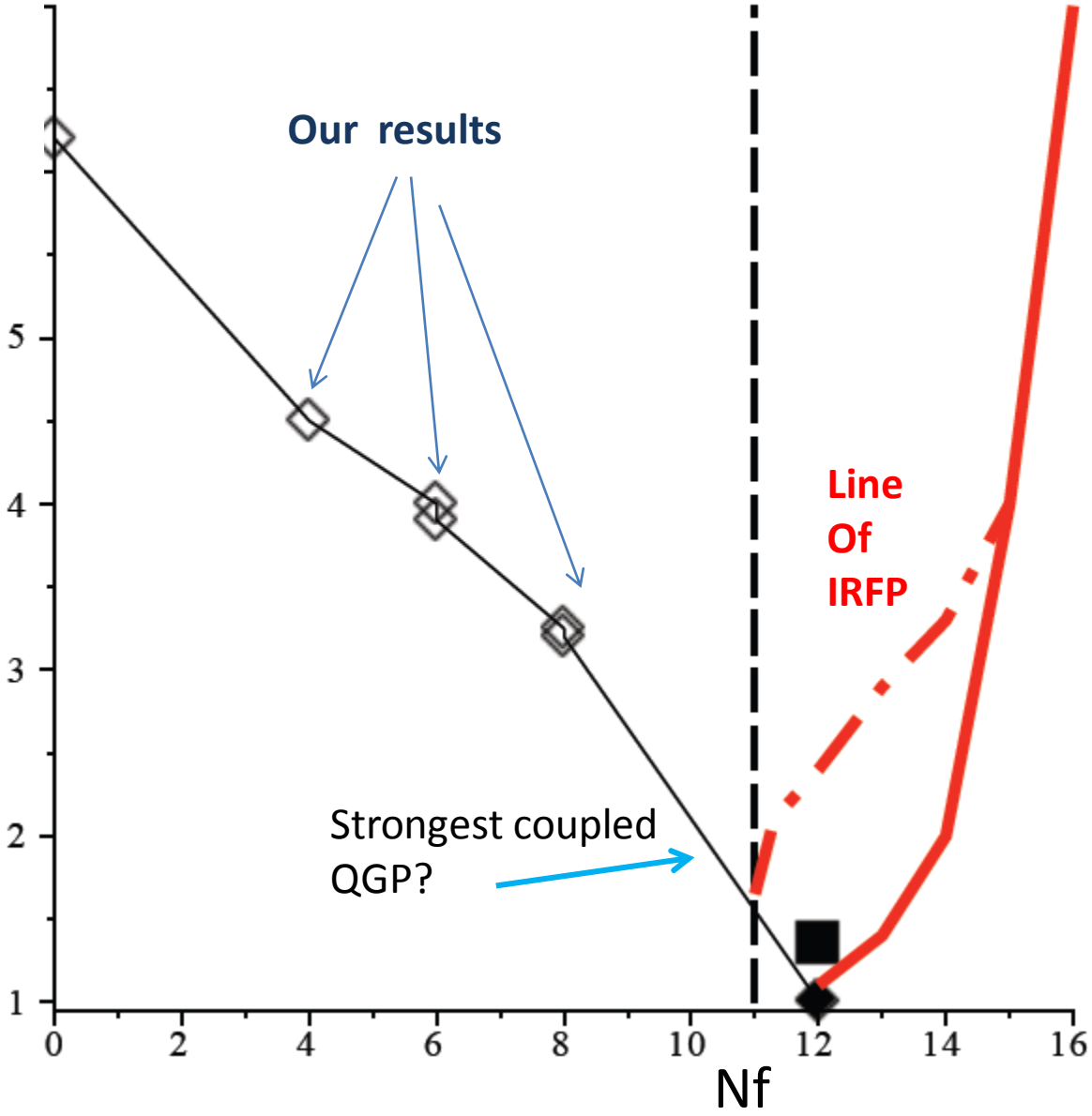


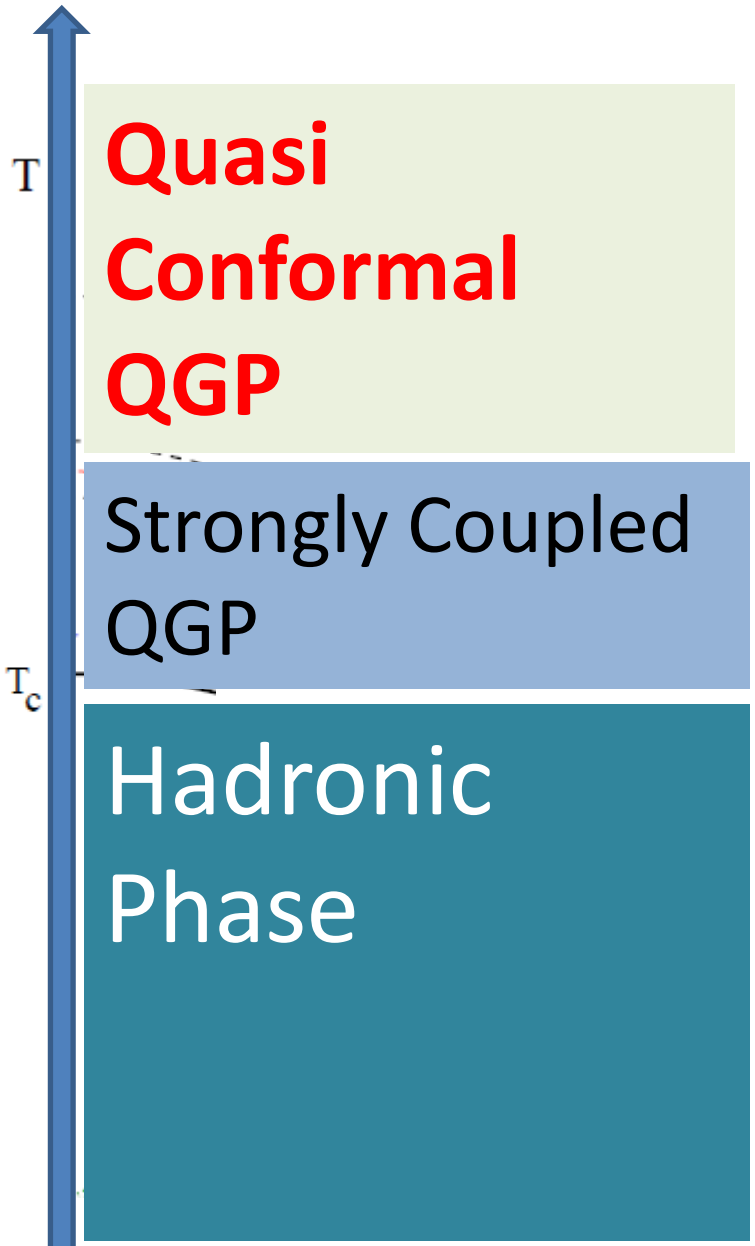
Alternative analysis

$$\beta_c(T_c) = \frac{2N_c}{g^2(T_c)}$$

Shuryak and Sulejmanpasic , 2012

Shuryak and Liao, 2012




T
Quasi
Conformal
QGP
Strongly Coupled
QGP
T_c
Hadronic
Phase

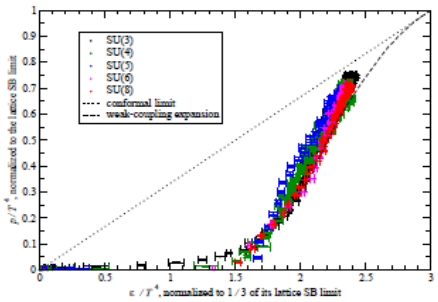
(Quasi)Conformality and High T QCD

$$\eta/S < (3 - 5) / 4\pi$$

AdS/CFT *vs.* lattice data in a 'quasi-conformal' regime

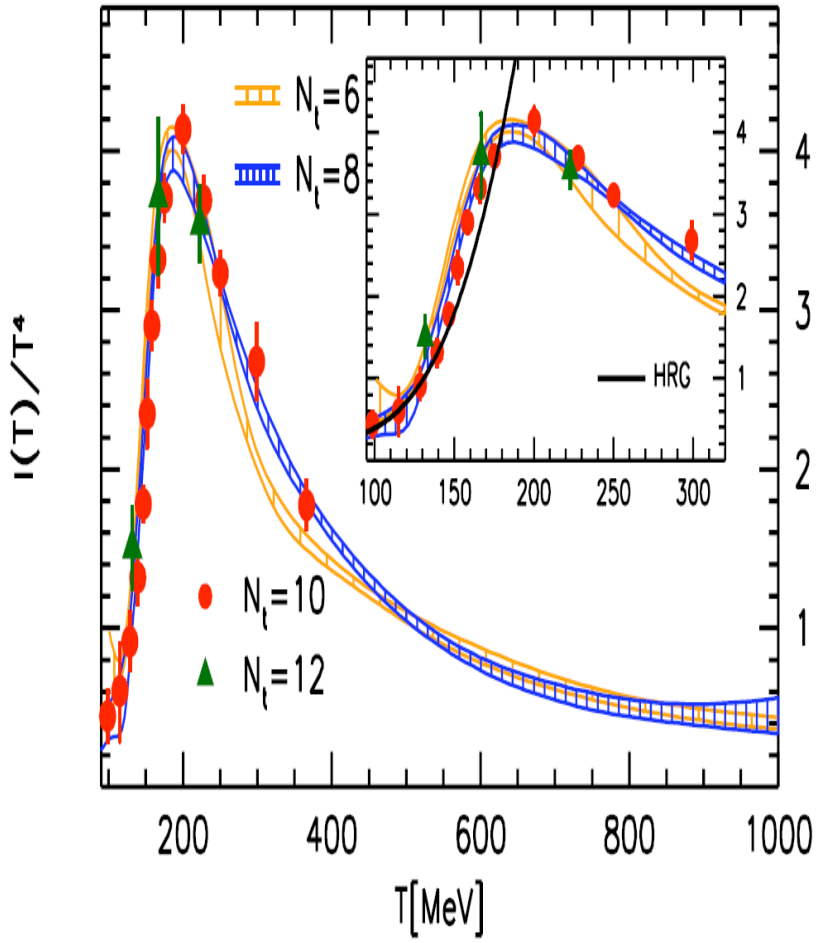
For $T \simeq 3T_c$, the lattice results reveal that the deconfined plasma, while still strongly interacting and far from the Stefan-Boltzmann limit, approaches a scale-invariant regime ...

$p(\varepsilon)$ equation of state and approach to conformality



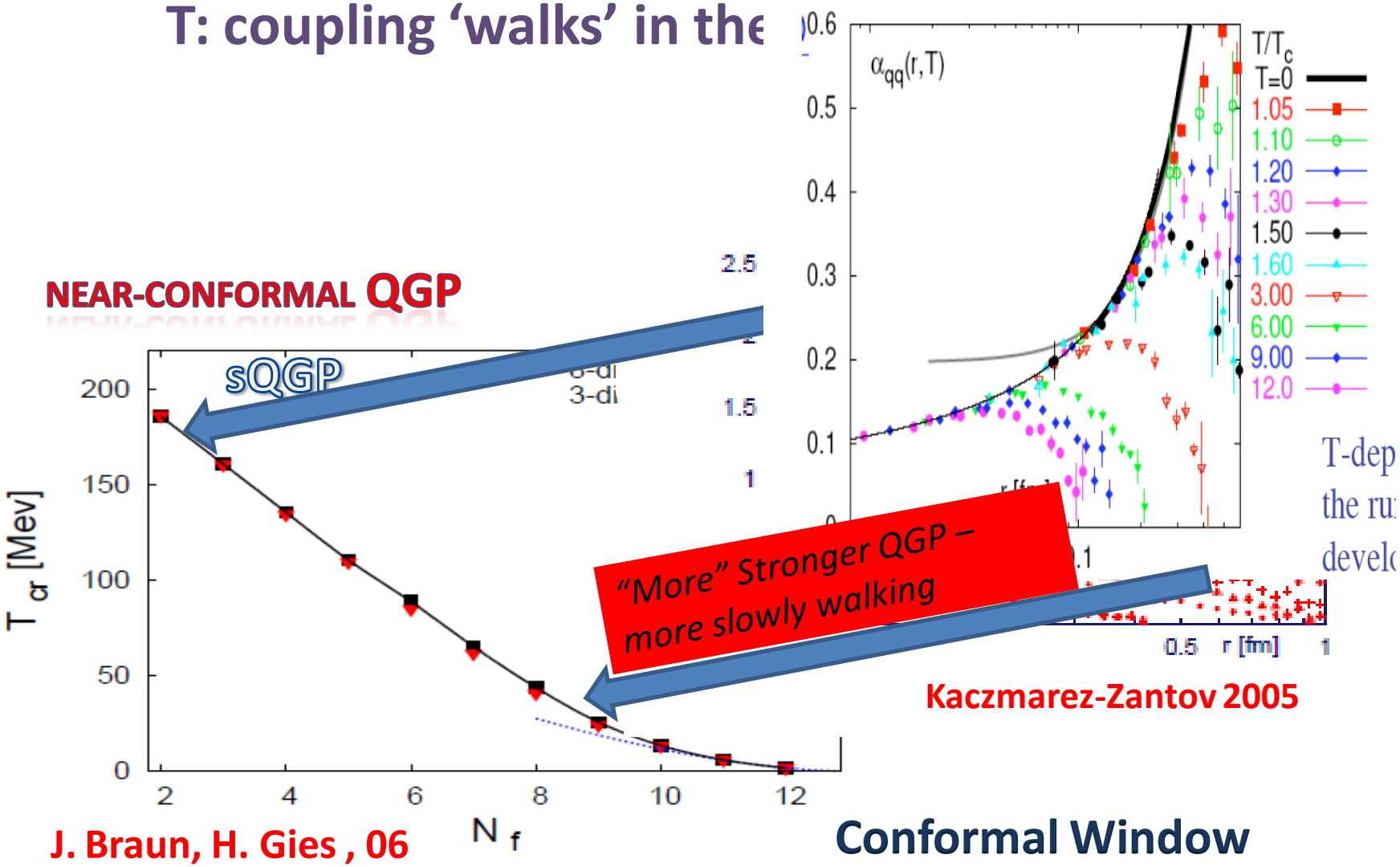
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

M. Panero 2010



S. Borsaniy et al.2011

Conformality and near-Conformality at zero and finite T: coupling 'walks' in the



J. Braun, H. Gies , 06

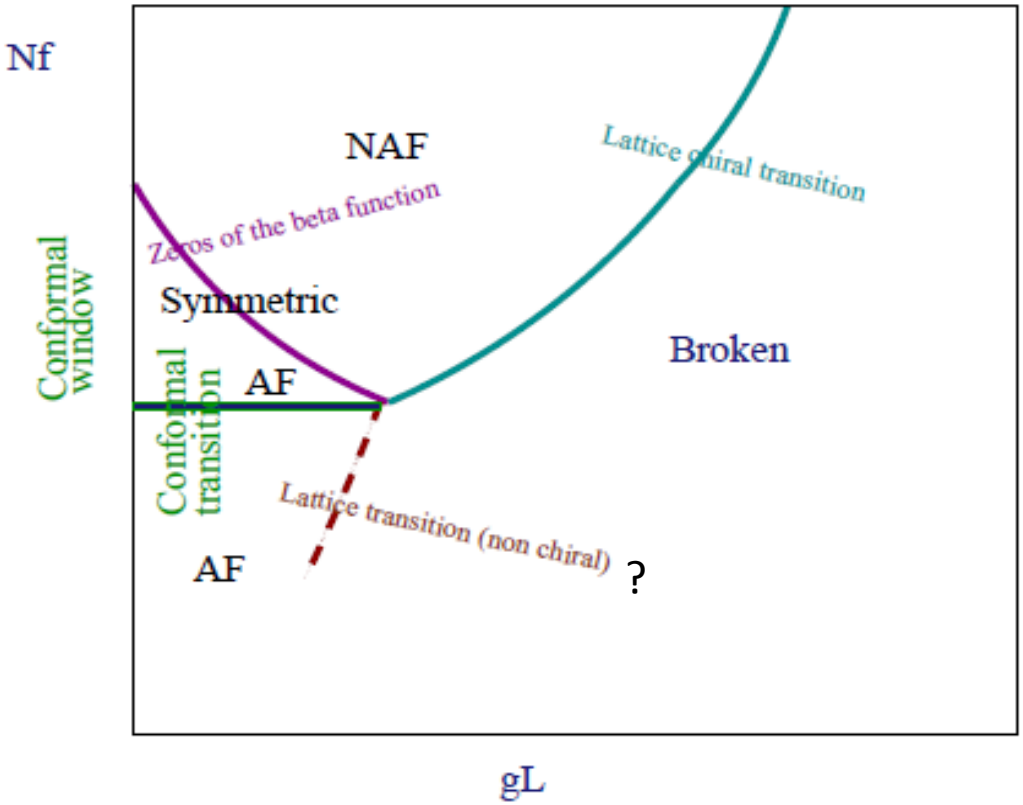
Kaczmarez-Zantov 2005

Conformal Window

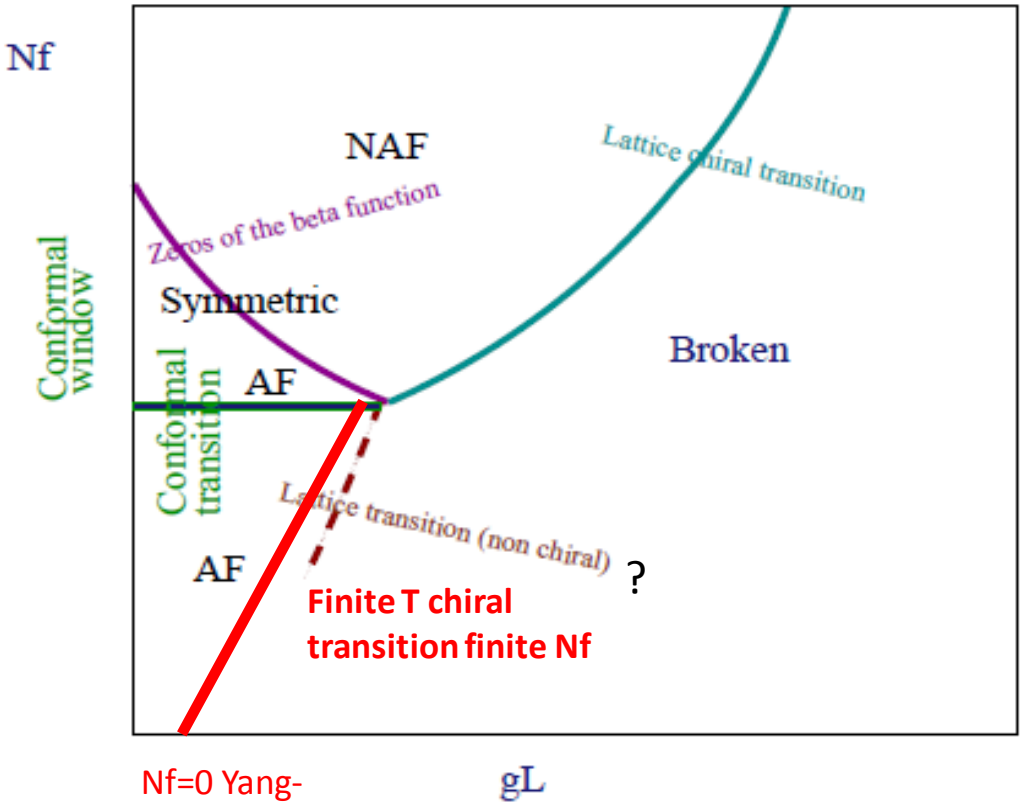
Towards Conformality-Lattice

PHASES OF QCD ON THE LATTICE : Temperature = 0

Miransky, Yamawaki

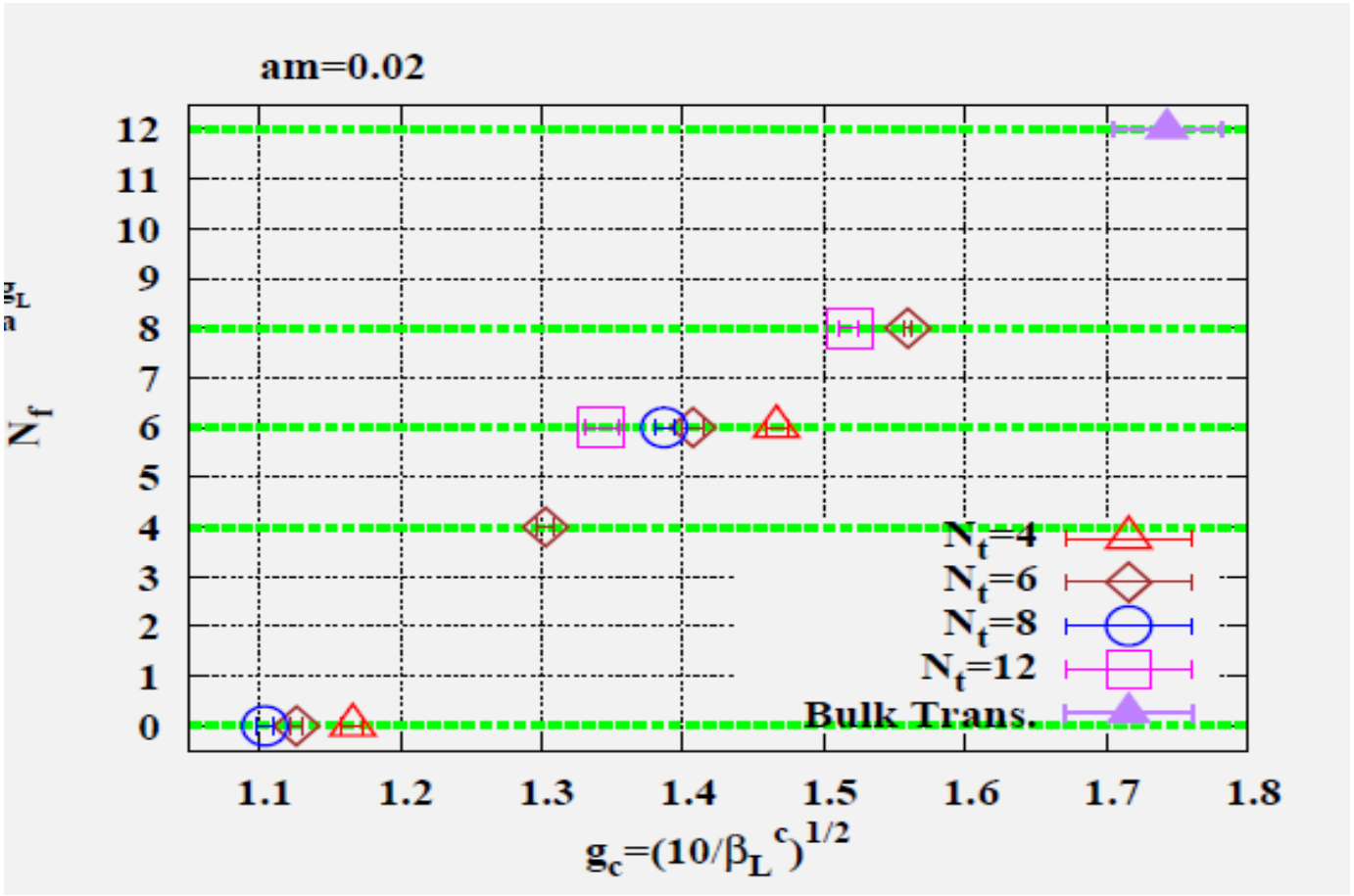


PHASES OF QCD ON THE LATTICE : Finite Nt



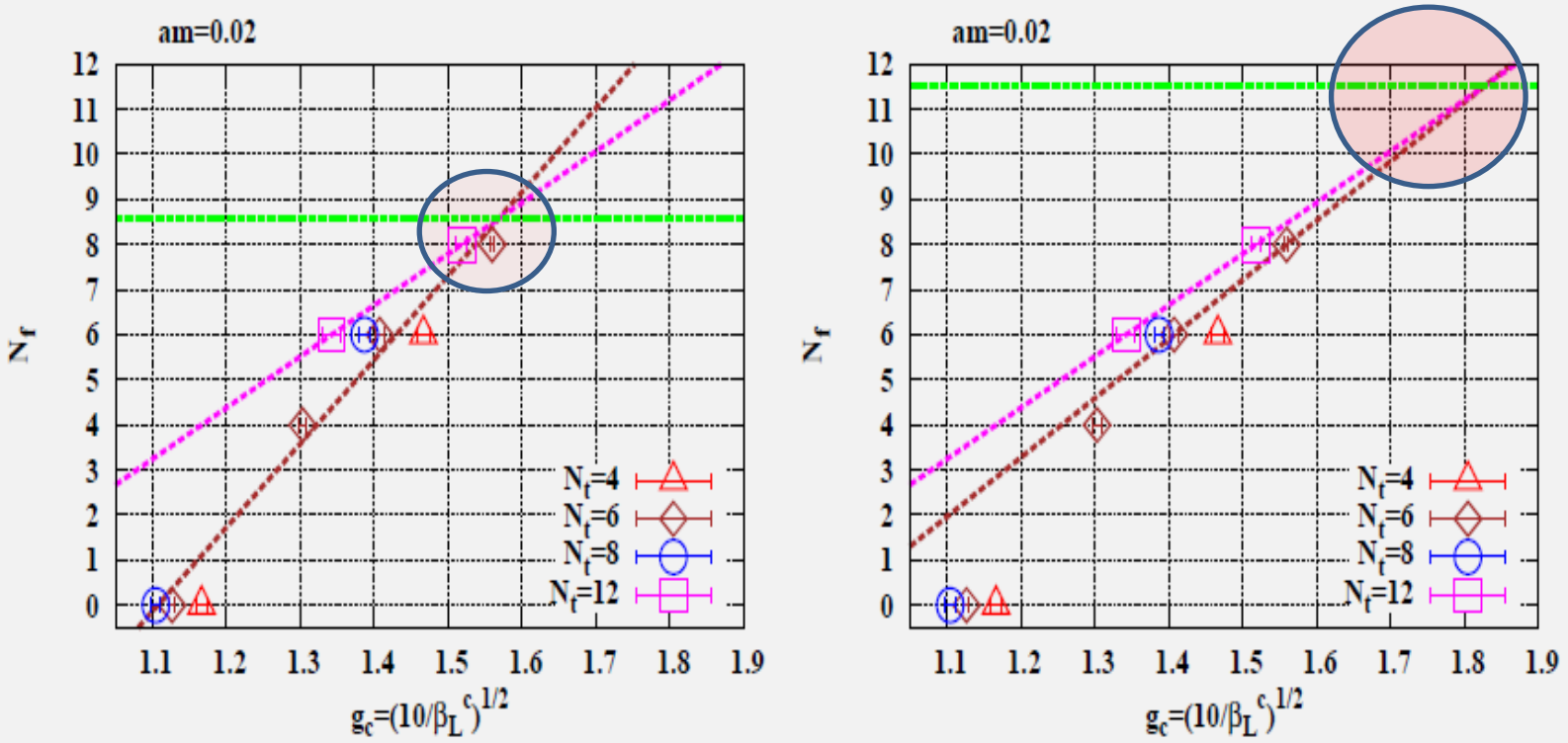
PHASES OF QCD ON THE LATTICE : Finite Nt

Numerical results



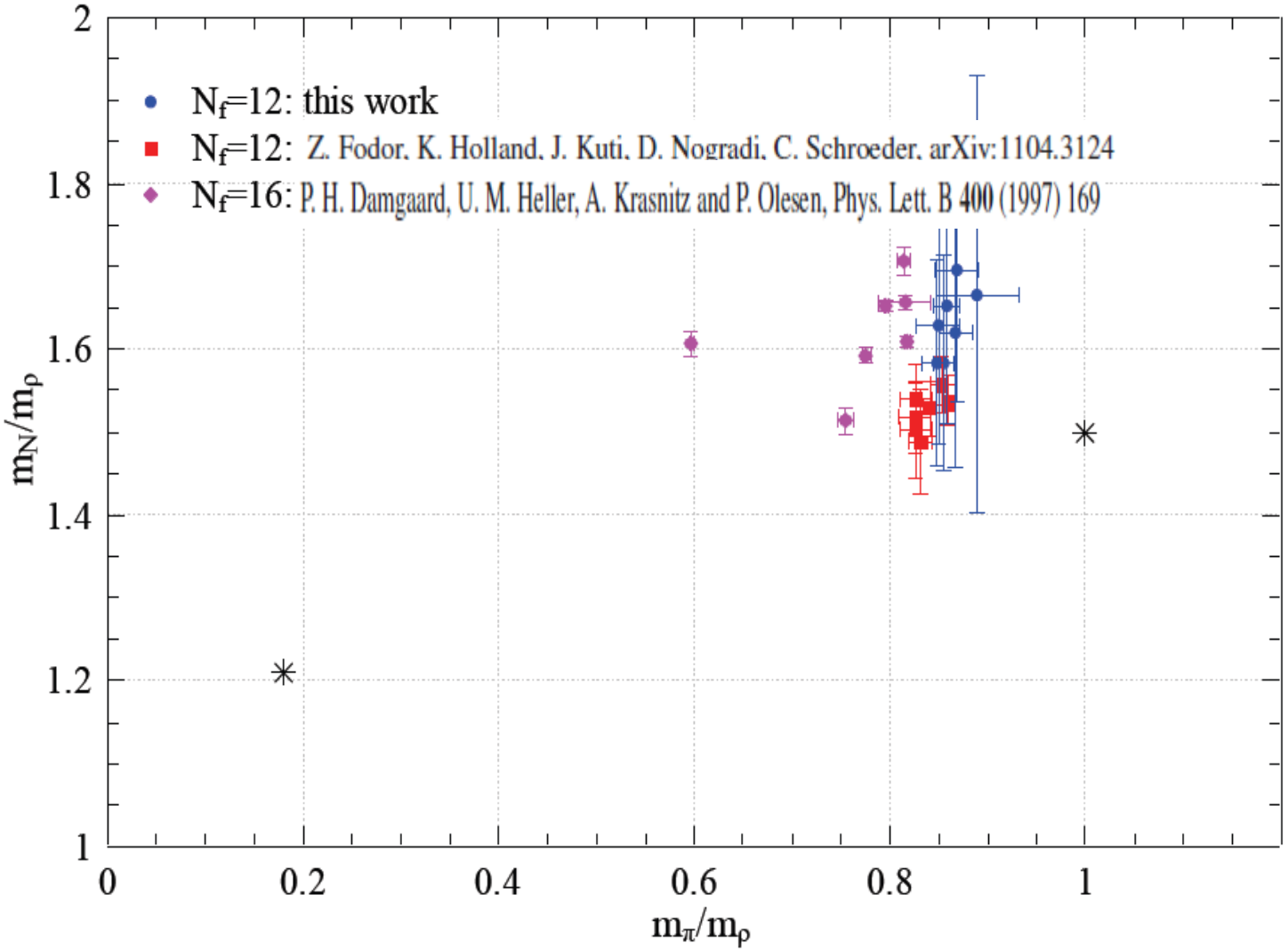
Critical number of flavor from thermal lines

N_{fc} = 10(2) *(preliminary)*

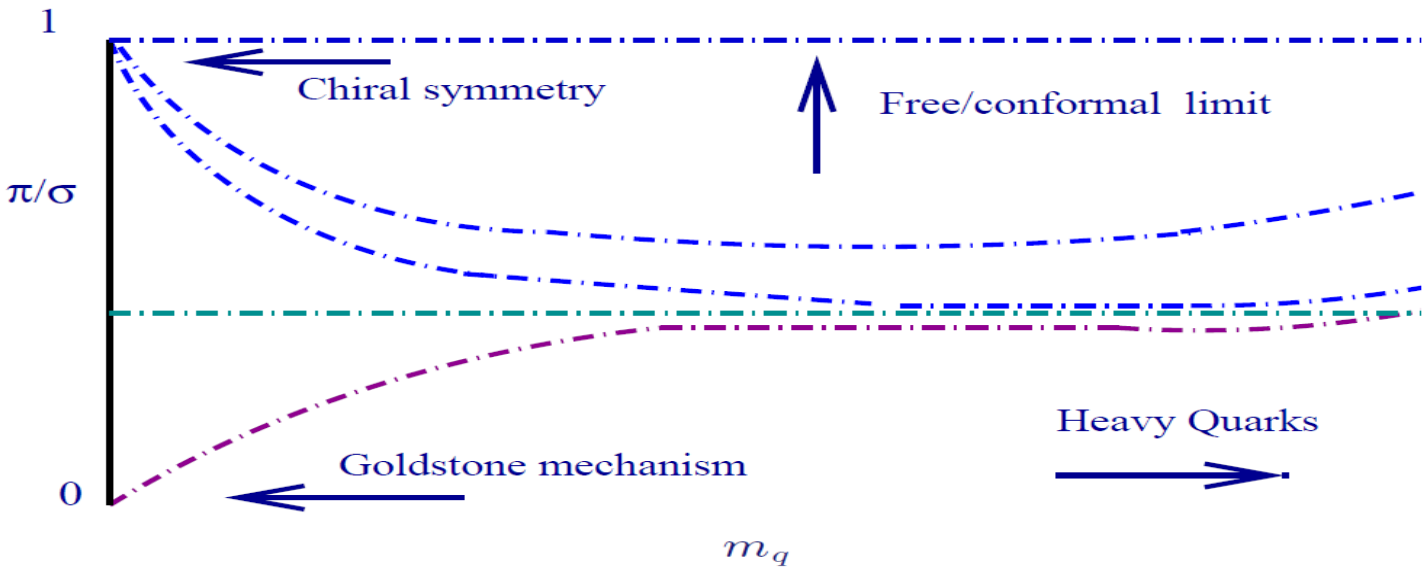


Inside the Conformal window

The nucleon mass and the 'Edinburgh Plot' in the conformal window



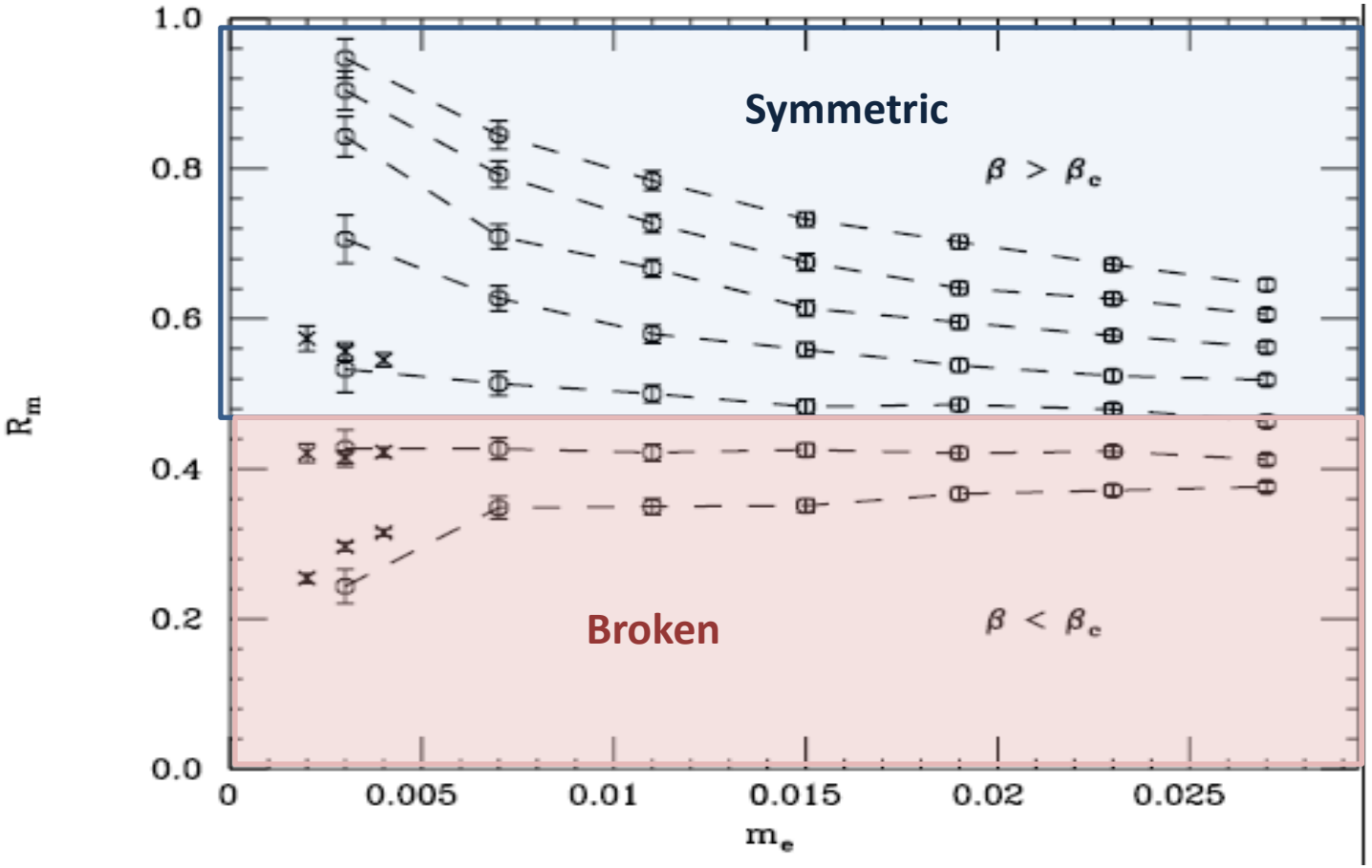
Mass ratio : qualitative features discriminating broken and symmetric phases



A sketchy view of the behavior of the π to σ mass ratio as a function of the bare mass. Each line corresponds to one lattice coupling, and the coupling decreases from bottom to top. Chiral symmetry is broken on the lower part

The transition of 4dQED on a Lattice

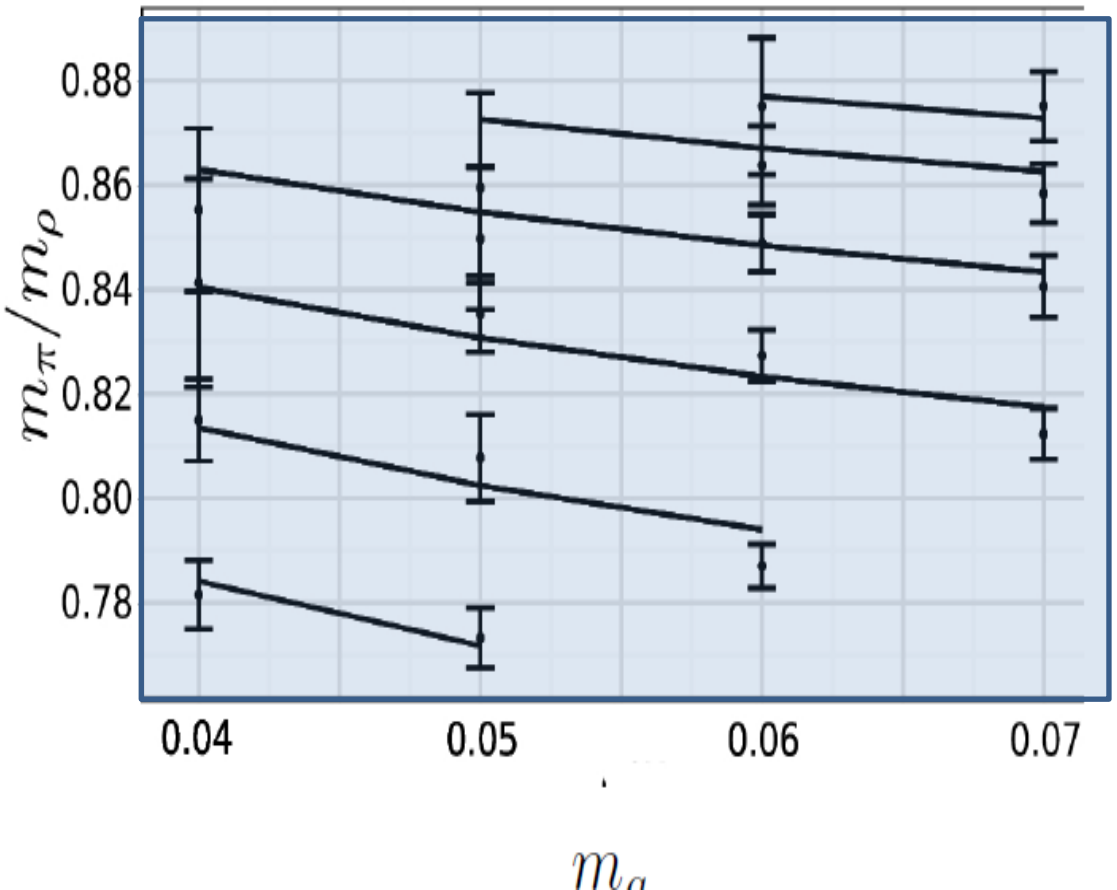
Kocic, Kogut, MPL, 1992



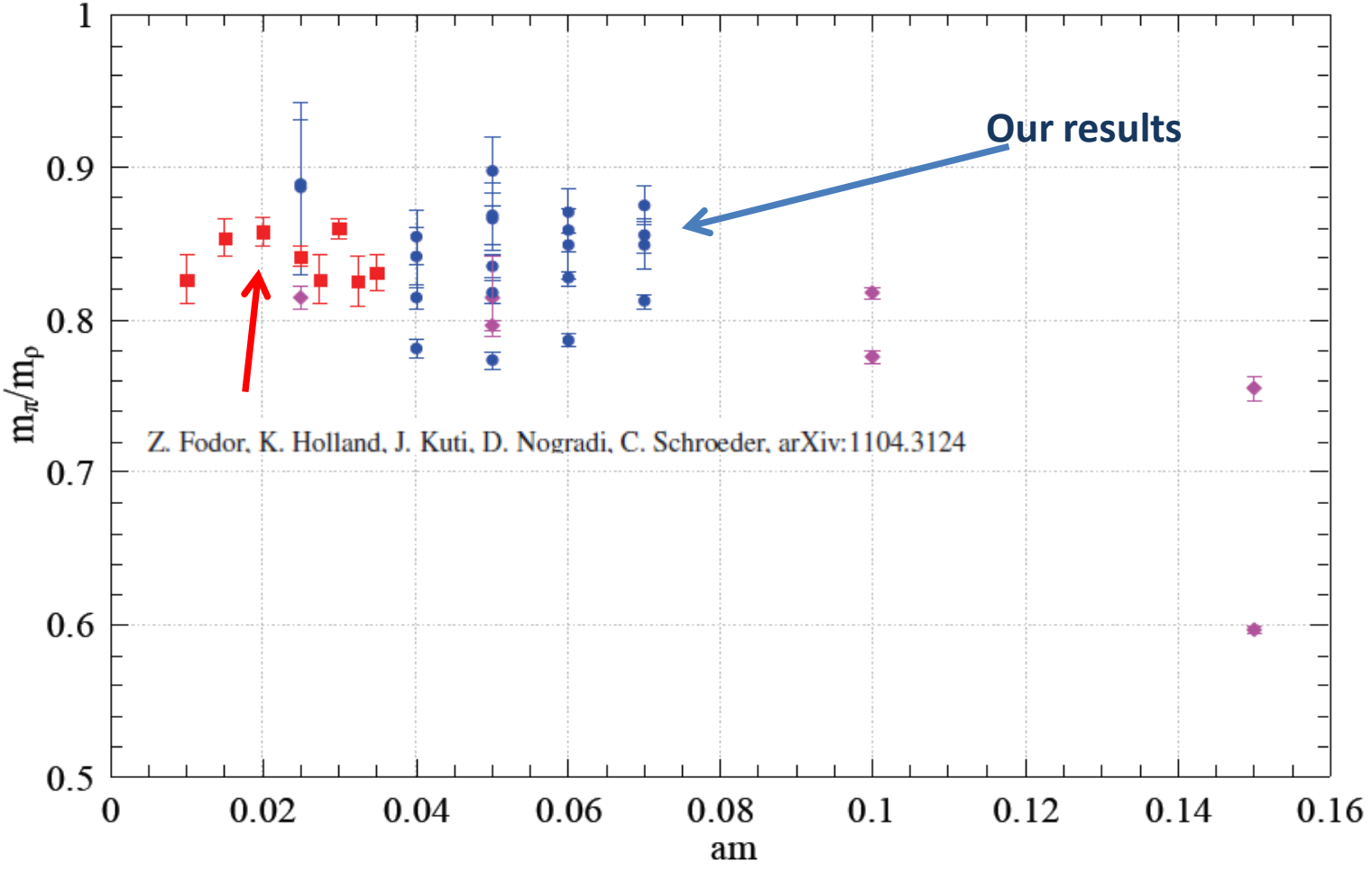
Nf = 12

SAME TREND AS IN SYMMETRIC QED, SUPPORTING SYMMETRIC PHASE

A. Deuzeman, M. P. Lombardo, E. Pallante, Phys. Rev. **D82** (2010) 074503



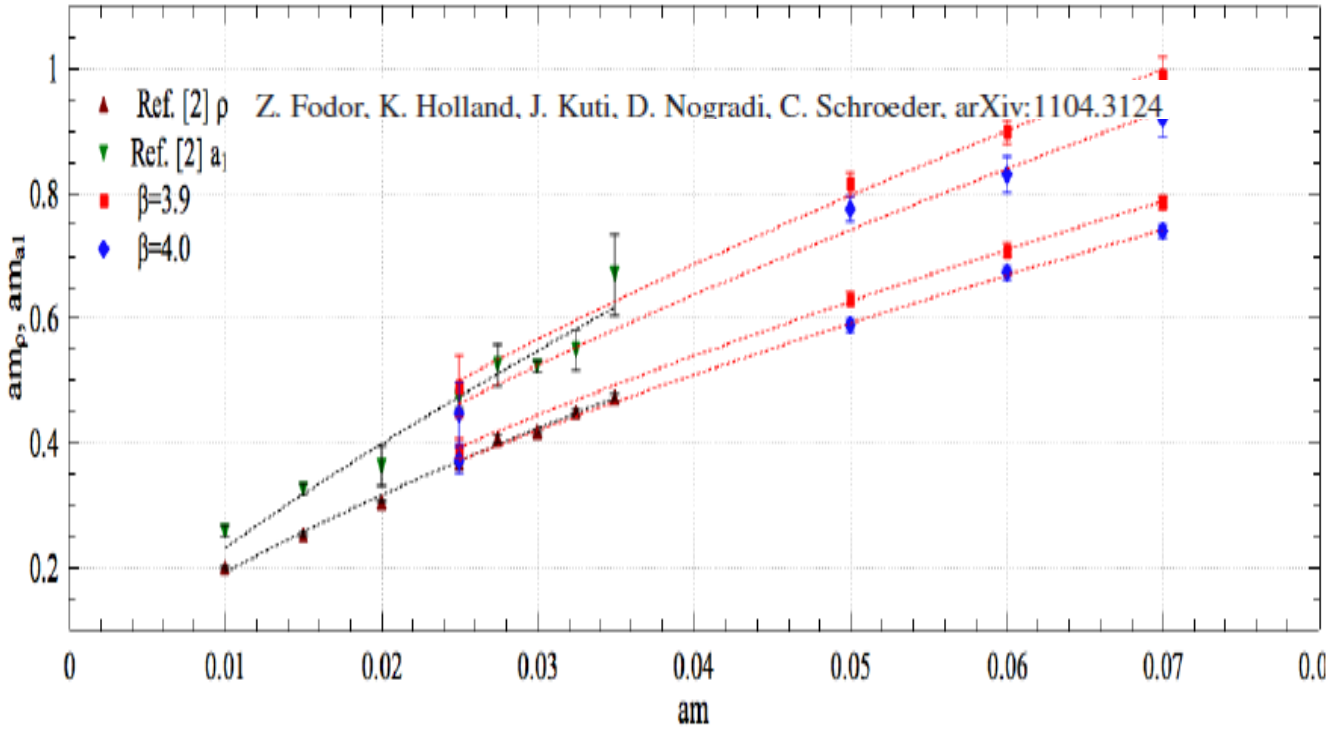
Nf=12: mass ratio



Chiral Partners, and anomalous dimension

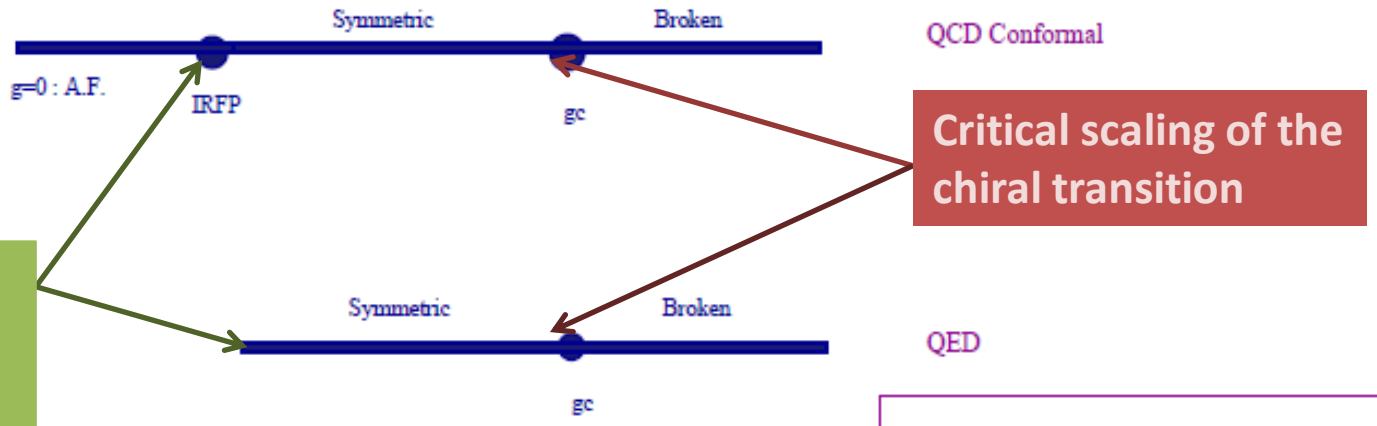
$$\delta_{a_1} = 0.67(4),\ \delta_\rho = 0.68(3),\ \text{at}\ \beta_L = 3.9$$

$$\delta_{a_1} = 0.68(7),\ \delta_\rho = 0.67(3)\ \text{at}\ \beta_L = 4.0,$$



Caveat... Can we compute anomalous dimenions away from IRFP ???

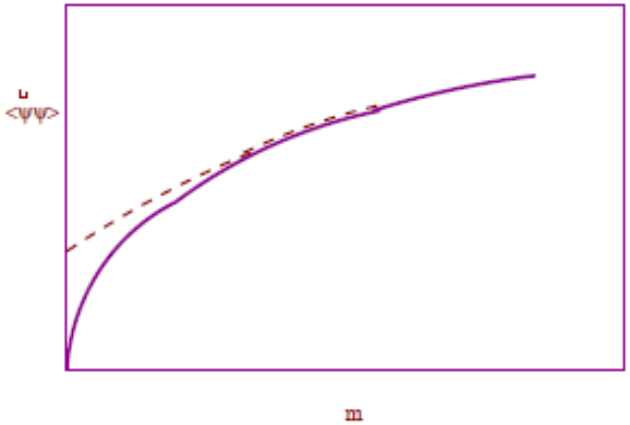
ANALOGY WITH STRONGLY COUPLED QED



Two Tasks:

1) **Chiral Symmetry vs Chiral Symmetry Breaking**

2) **If we measure an anomalous dimension, is this associated to Chiral or Conformal Symmetries?**



Lattice strategy:
–Contrast χ^2 of different fits –

- Symmetric Phase $\langle\bar{\psi}\psi\rangle = am^d$
- Broken Phase $\langle\bar{\psi}\psi\rangle = am + b$

Summary

Near-conformal dynamics (continuum):

Tc/Λ suggests scale separation for Nf > 6
Pre-conformal (critical) behaviour

$$T_c(N_f) = K|N_f - N_f^c|^{-1/\theta} .$$

observed for Nf > 6, with **Nf critical = 11 (3)**
Shuryak's (equivalent) view : coupling at (Tc, Nfc) = coupling at IRFP

Near-conformal dynamics (lattice) :

Thermal pseudocritical lines meet at (g*, Nf critical),
with **Nf critical = 10(2)** (preliminary)

All estimates confirm that twelve flavors is close to the conformal transitions – Nf=12 difficult to study directly (as we know!)

Interesting interplay with finite temperature QCD with implications for the physics of the strongly interactive quark gluon plasma