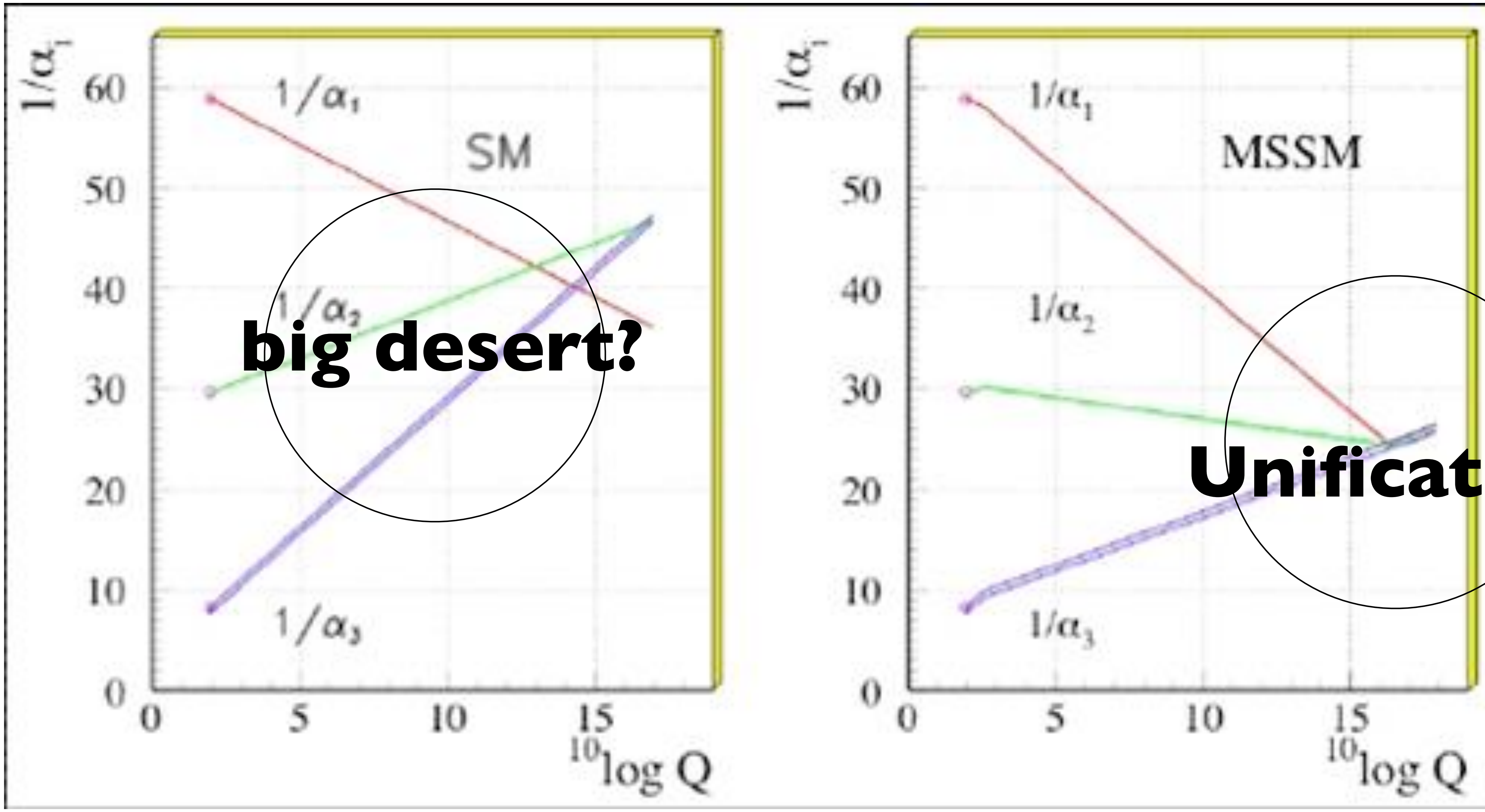
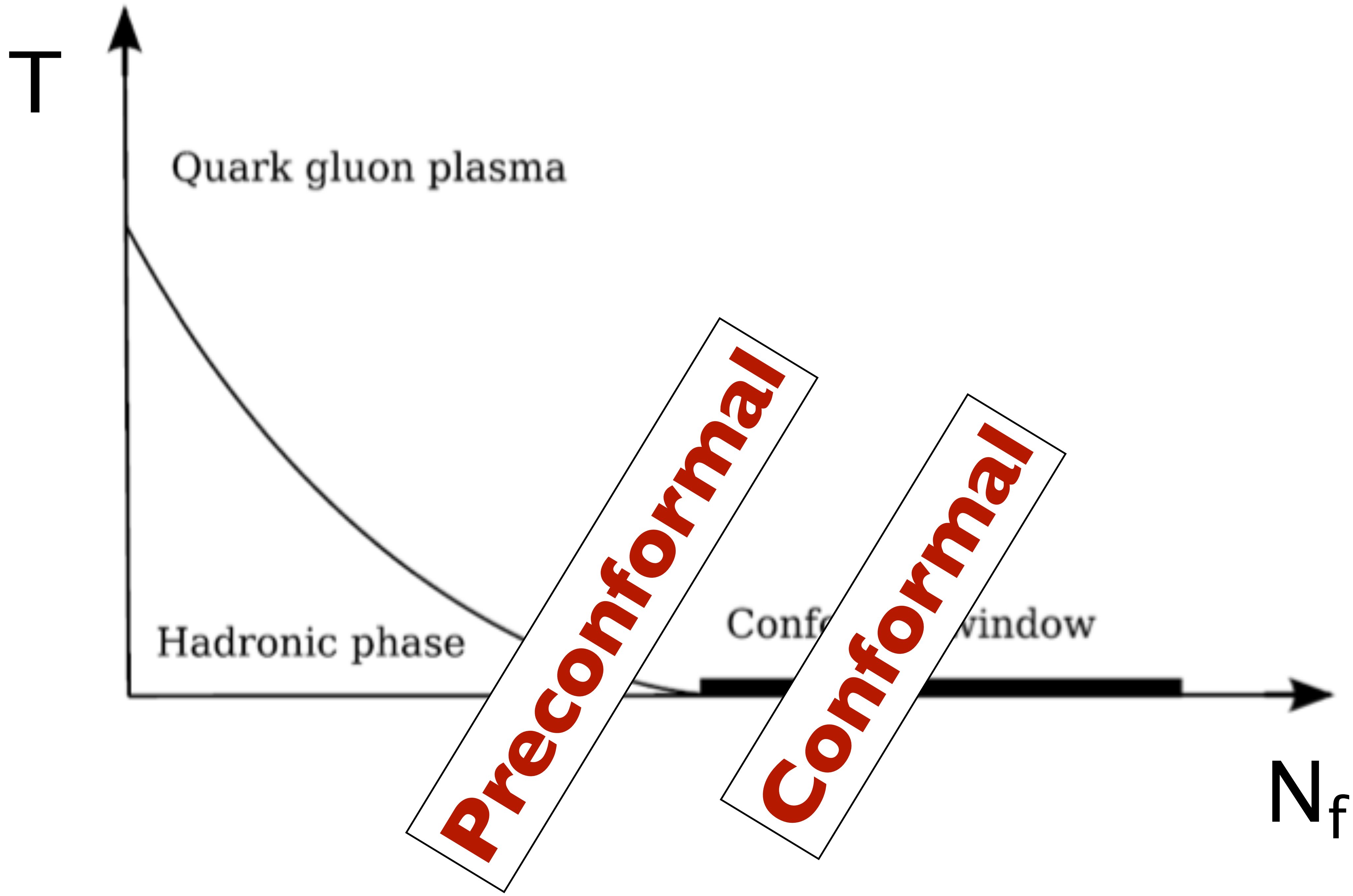
Out
In &
of the
Conformal Window

Based on work with: A. Deuzeman, M.P. Lombardo, K. Miura,
T. Nunes da Silva (lattice) A. Barranco, J. Russo (AdS/CFT)

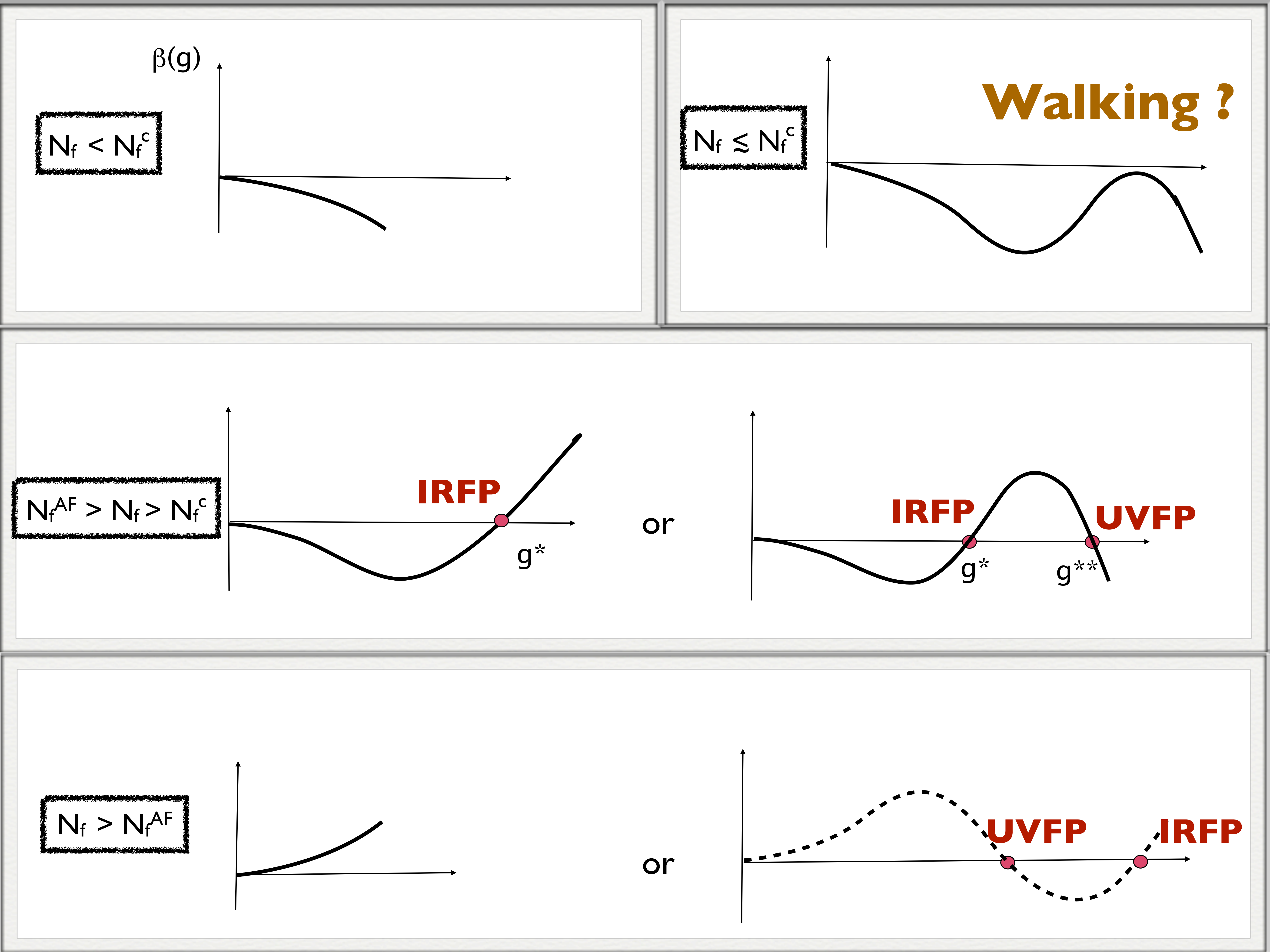


Does conformal symmetry play a role well above the EWSB scale?

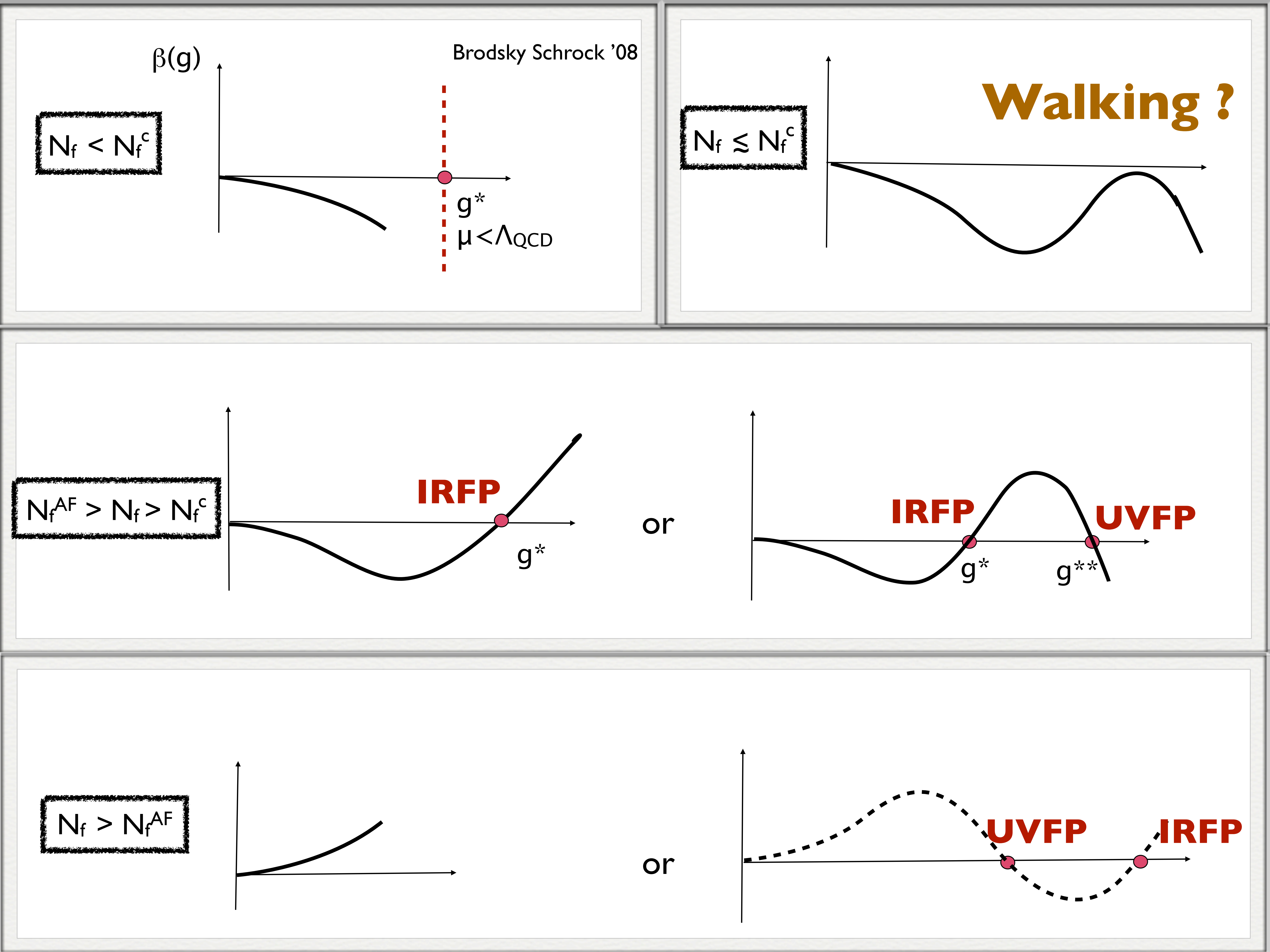
The Conformal Window



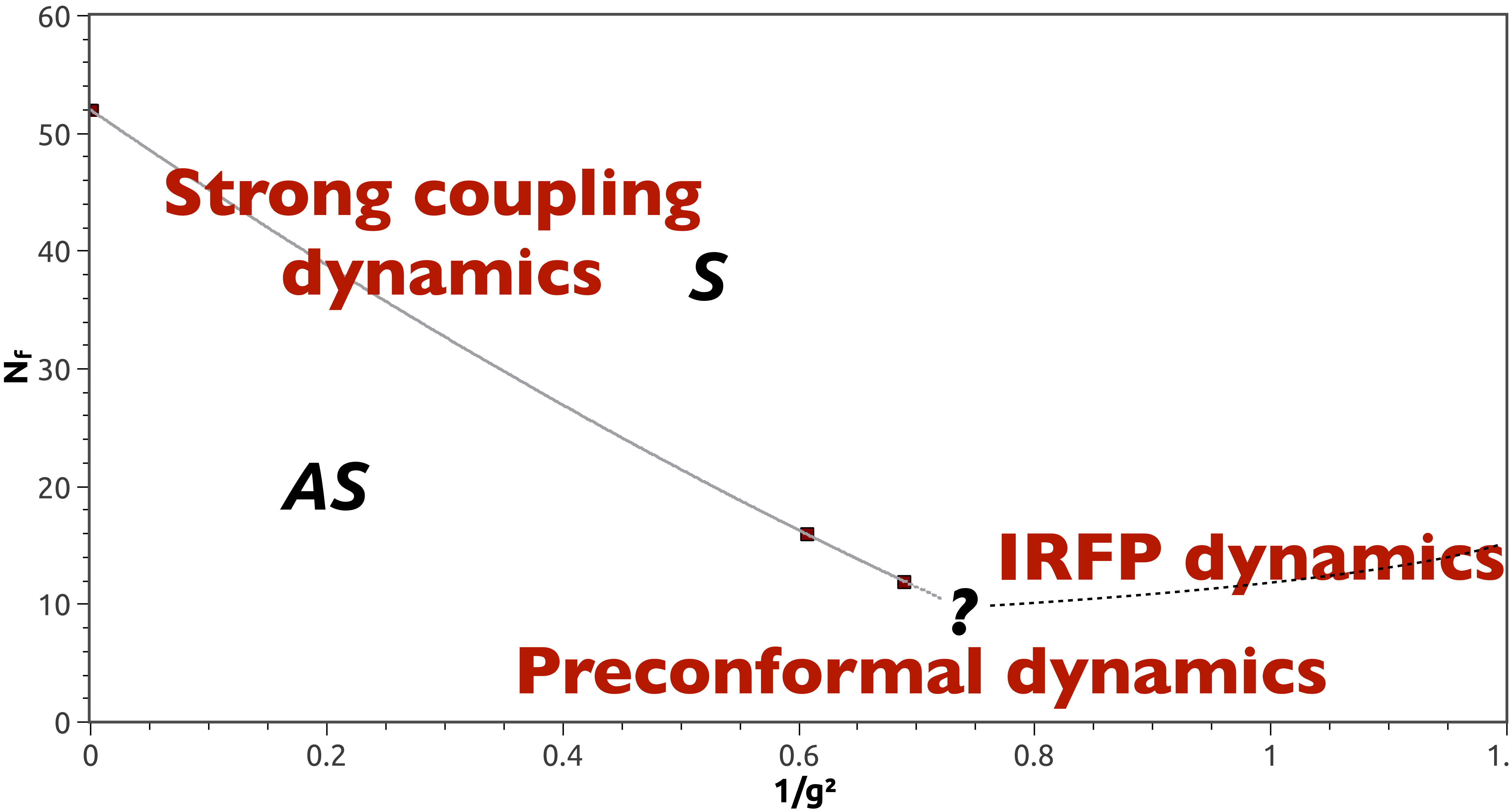
✓quark gluon plasma (QGP): high T - low Nf
✓preconformal regime (T=0, low T - high Nf)
✓conformal regime (T=0)



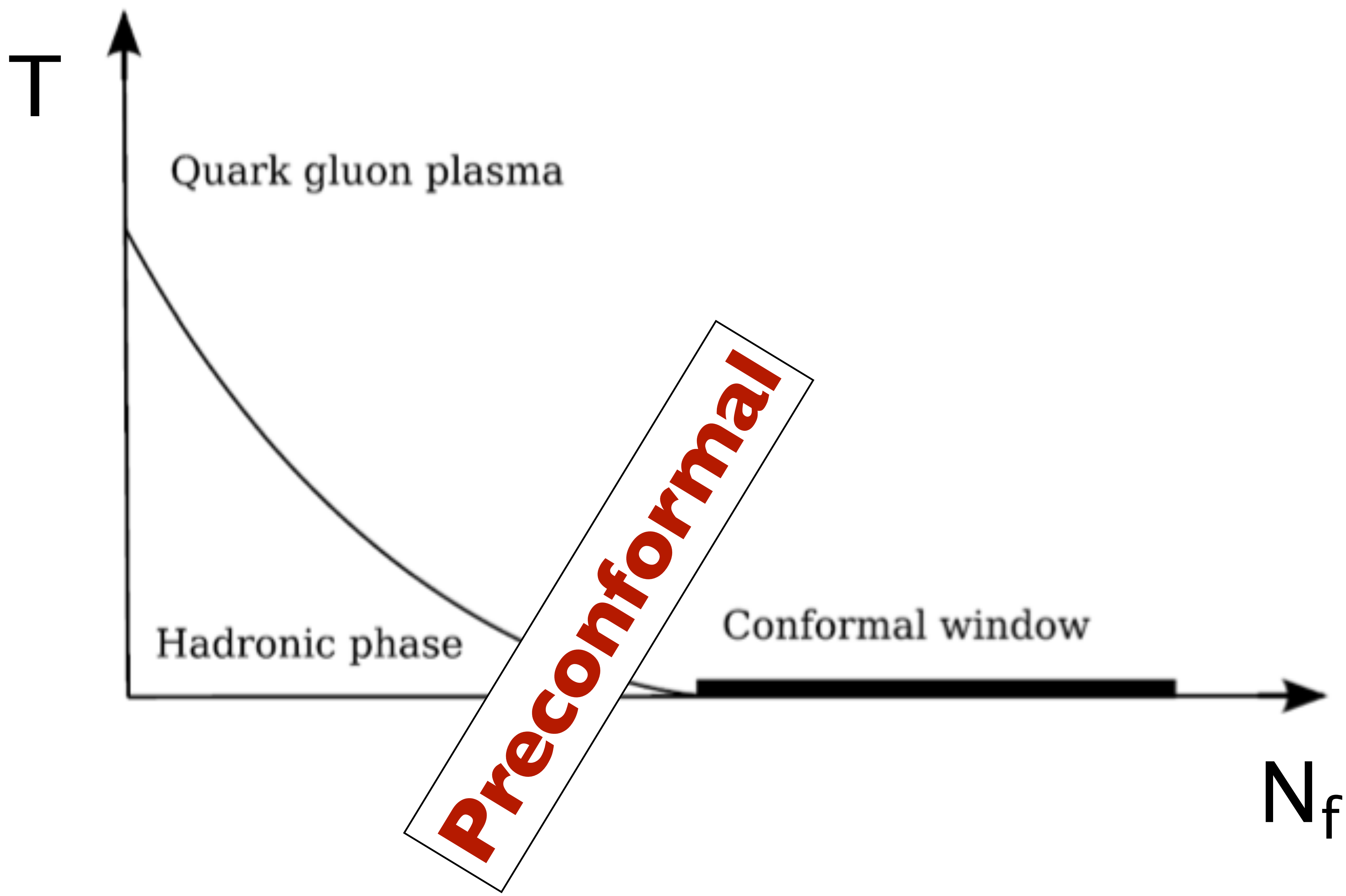
β(g)
$N_f < N_f^c$
$N_f \lesssim N_f^c$
Walking ?
$N_f^{AF} > N_f > N_f^c$
IRFP
g*
or
IRFP
UVFP
g*
g**
$N_f > N_f^{AF}$
or
UVFP
IRFP


β(g)
Brodsky Schrock '08
Nf < Nf^c
g*
μ<ΛQCD
Walking ?
Nf ≲ Nf^c
Nf^AF > Nf > Nf^c
IRFP
g*
or
IRFP
UVFP
g*
g**
Nf > Nf^AF
or
UVFP
IRFP

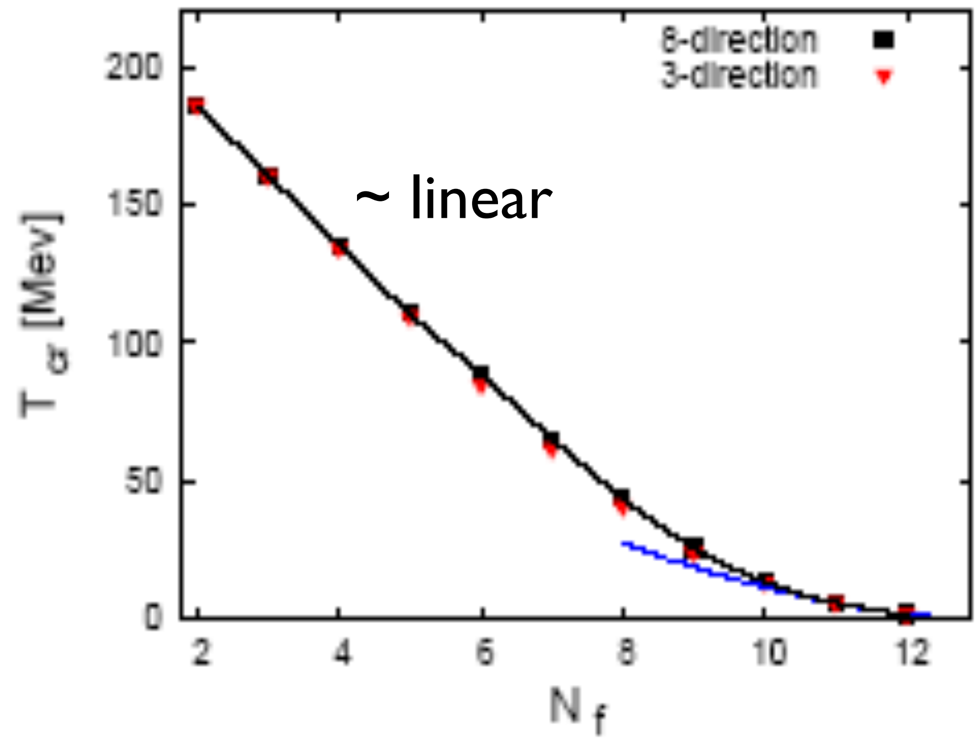
[Deuzeman,Lombardo,Nunes EP '12]



Preconformal Dynamics



T
Quark gluon plasma
Hadronic phase
Preconformal
Conformal window
N_f



Braun, Gies ’06
Braun, Fischer, Gies ’10

$$k_{\rm SB} \propto k_0\,\theta(N_f^{\rm cr}-N_f)\,|N_f^{\rm cr}-N_f|^{-1/\Theta}\exp\left(-\frac{\pi}{2\epsilon\sqrt{\alpha|N_f^{\rm cr}-N_f|}}\right)$$

$\bar{\psi}\psi$,Tc

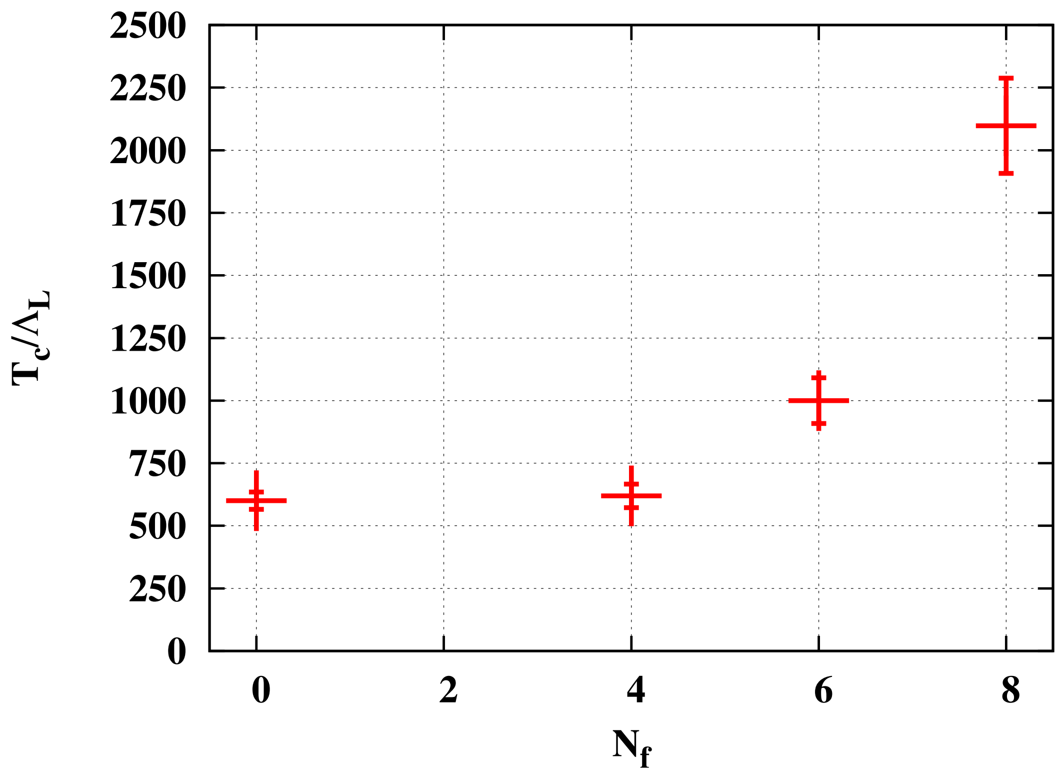
power-law
(due to running coupling)

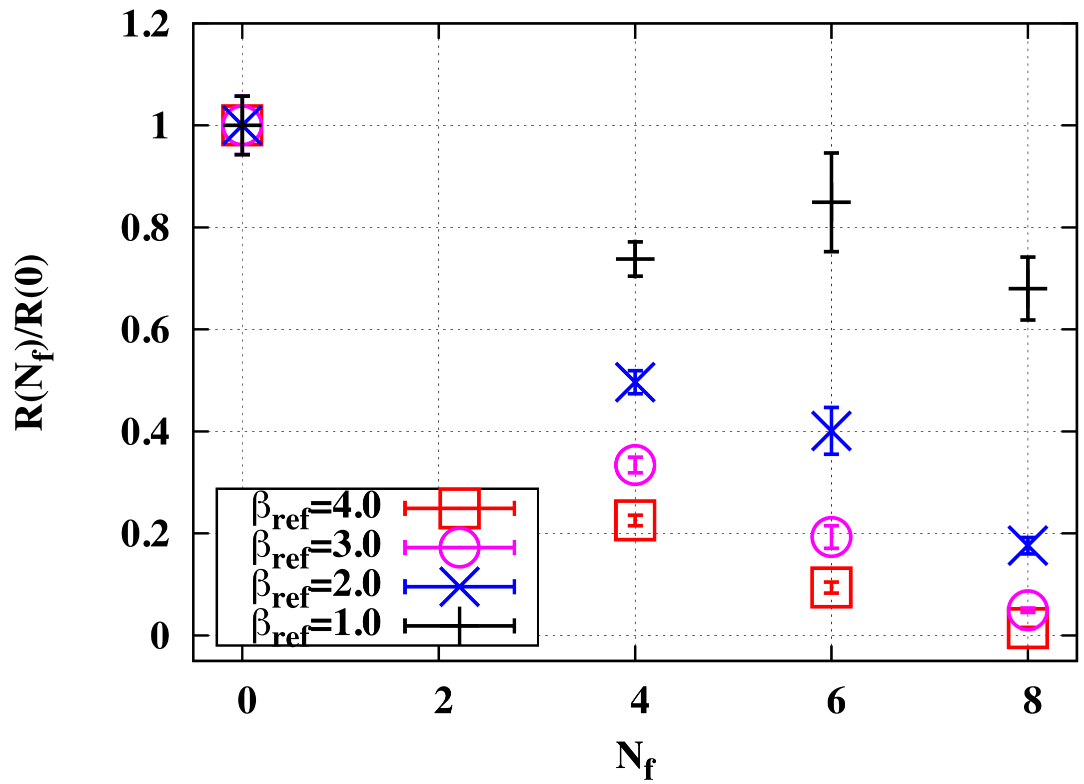
exponential-law
(Miransky-KBT scaling)

$$\beta(g^2) = -\Theta(g^2-g_\star^2)+\ldots \quad \Theta<0$$

From a IR scale to a UV scale

[Miura, Lombardo, EP '11]





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

UV → IR →
$$\frac{\Lambda_{\rm ref}}{\Lambda_{\rm L}} = \exp\left[\frac{\beta_{\rm L}^{\rm ref}}{4N_c b_0}\right]$$

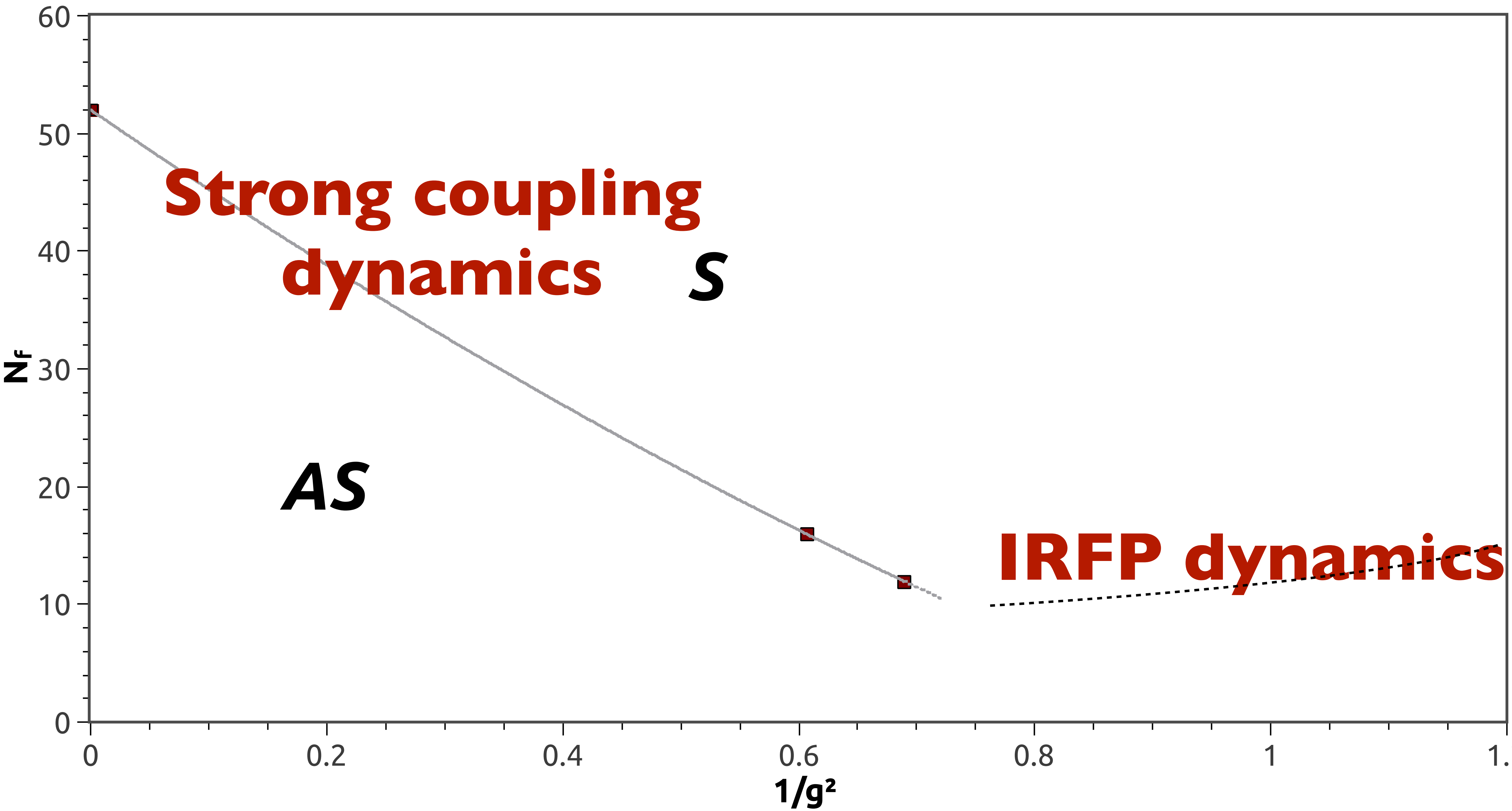
Very rough extrapolation

$N_f^c = 11(2)$ for $\beta_{\rm L}^{\rm ref} = 2$ $\quad 1.1 < 1/|\theta| < 2.5$

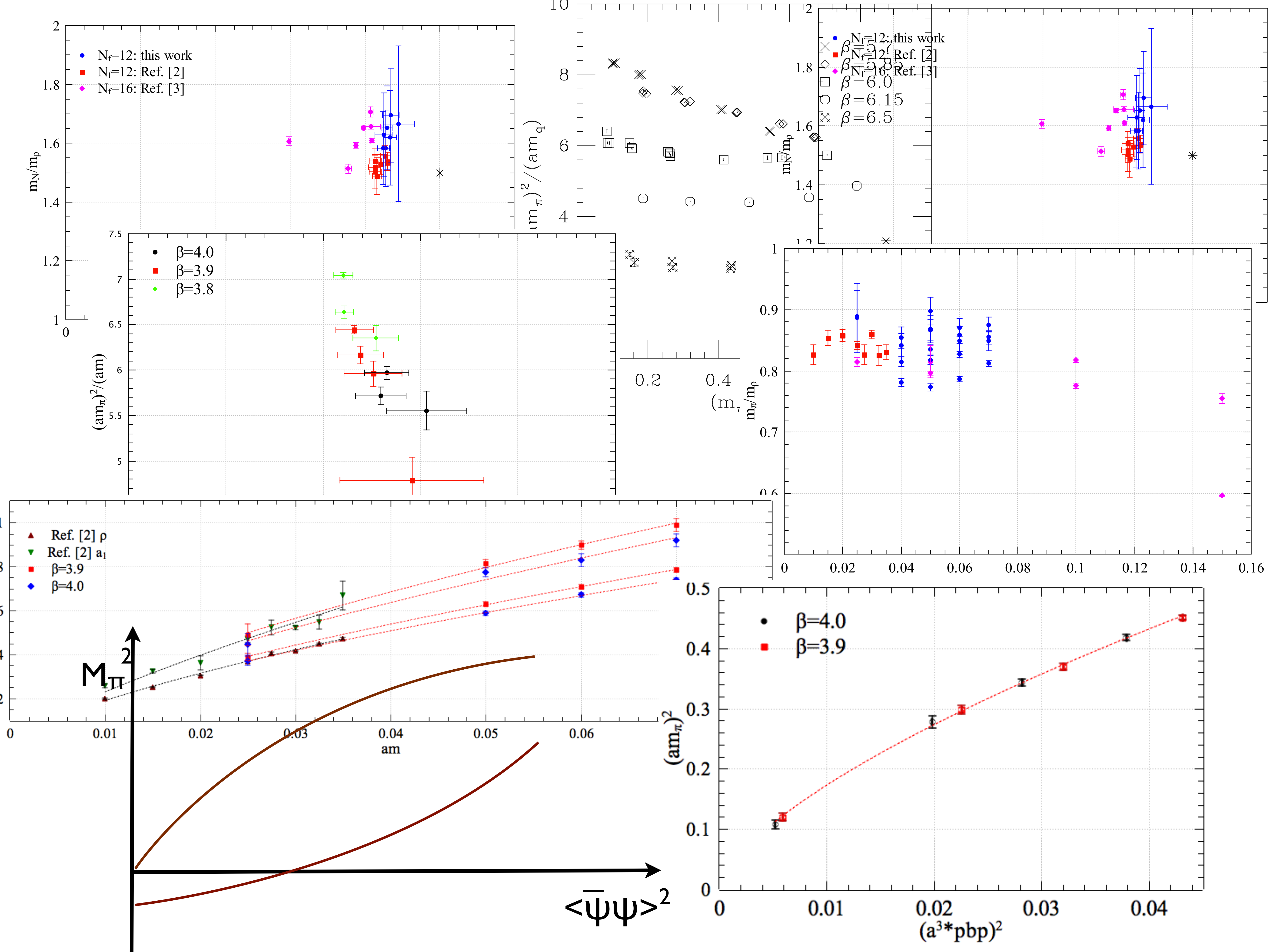
$N_f^c = 9(1)$ for $\beta_{\rm L}^{\rm ref} = 4.0$

Inside the Conformal Window

[Deuzeman,Lombardo,Nunes EP '12]



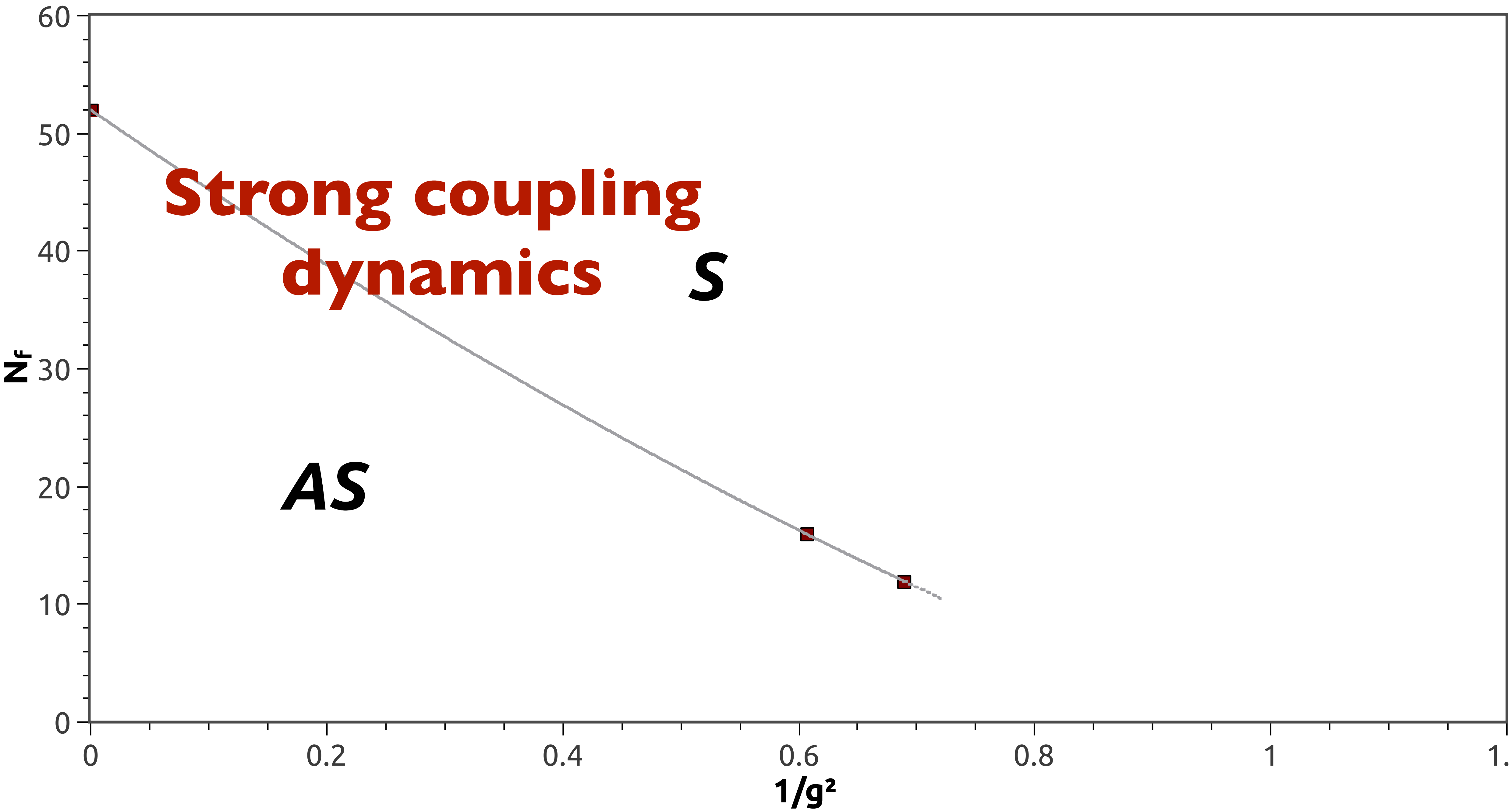
The Spectrum



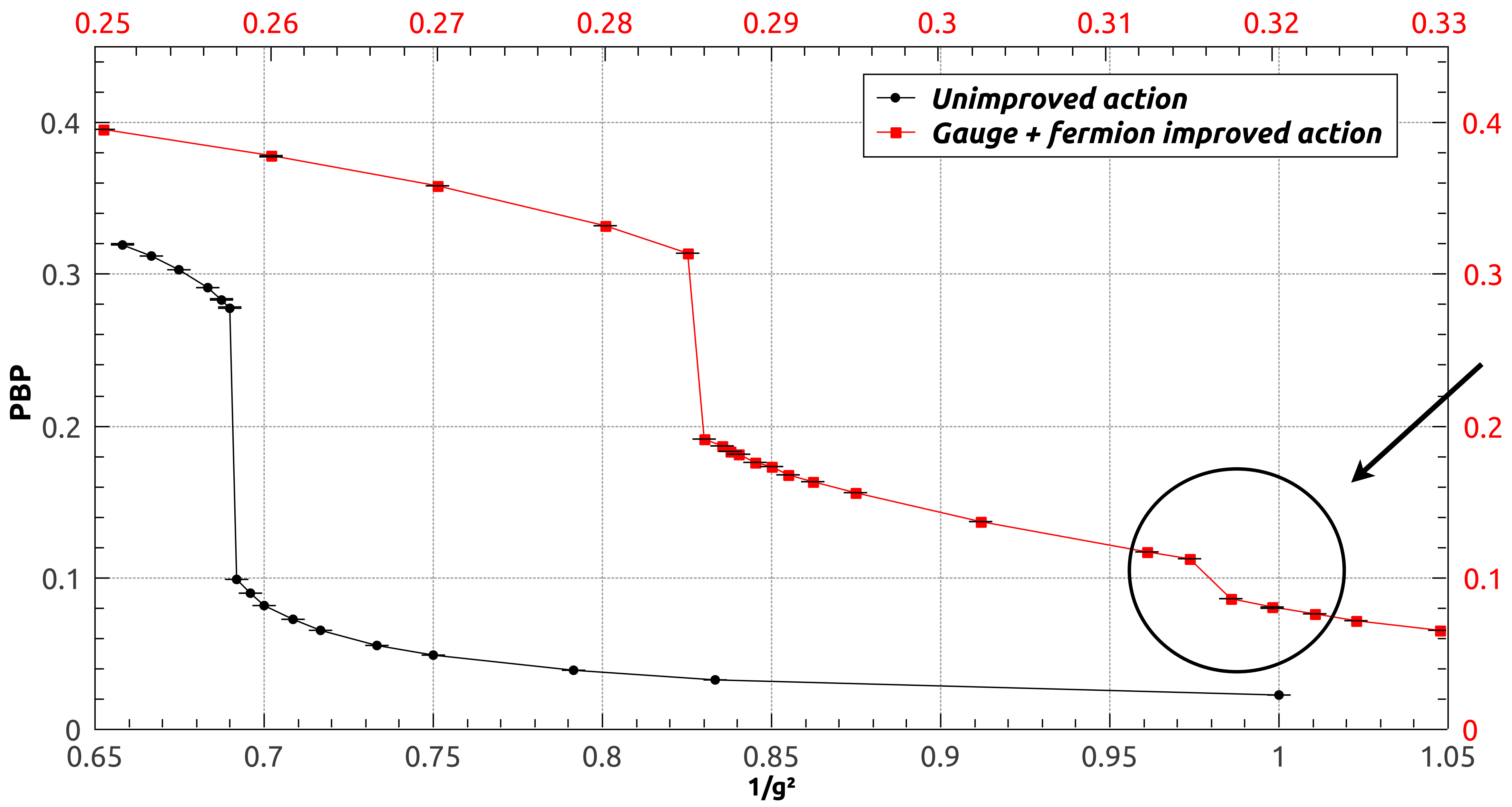
N_f=12: this work
N_f=12: Ref. [2]
N_f=16: Ref. [3]
m_N/m_ρ
β=4.0
β=3.9
β=3.8
(am_π)^2/(am)
β=5.7
β=5.85
β=6.0
β=6.15
β=6.5
(am_π)^2/(am_q)
m_π/m_ρ
Ref. [2] ρ
Ref. [2] a_1
am
M_π^2
<ψ̄ψ>^2
(am_π)^2
(a^3*pbp)^2

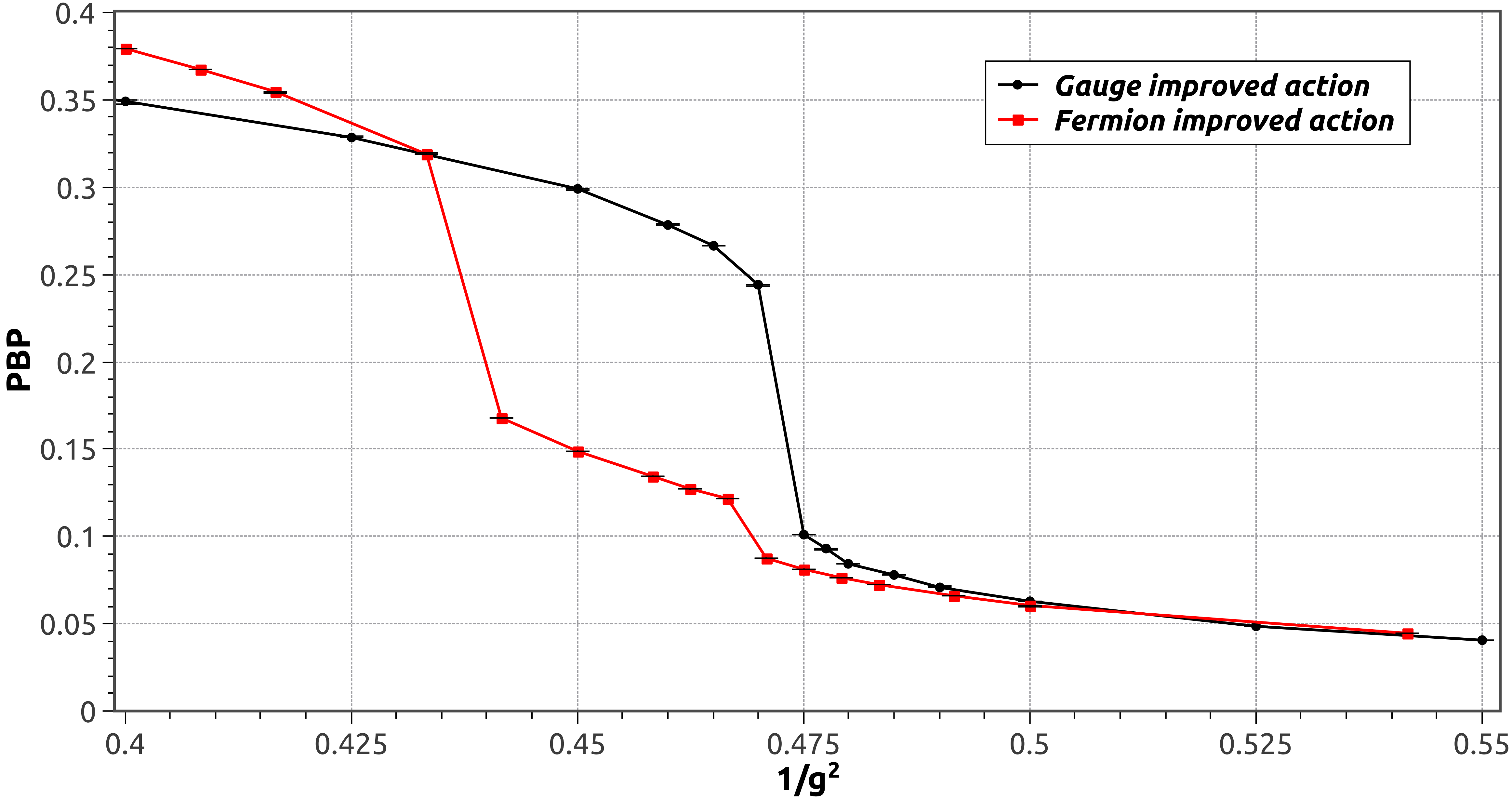
Strong coupling dynamics and bulk transitions

[Deuzeman,Lombardo,Nunes EP ’12]



The bulk transition(s)





Gauge improved action
Fermion improved action
PBP
1/g^2
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.4
0.425
0.45
0.475
0.5
0.525
0.55

Symanzik improvement @ strong coupling

Gauge action:

$$S_G = \beta_0 \,\mathrm{Re}(1 - \underbrace{U(1\times 1)}_{\text{nearest neighbor}}) + \beta_1 \,\mathrm{Re}(1 - \underbrace{U(2\times 1)}_{\text{next-to-nearest neighbor}}) \qquad \beta_0 = \frac{5}{3}\beta, \;\; \beta_1 = -\frac{1}{12}\beta \qquad \beta = \frac{6}{g^2}$$

nearest neighbor   next-to-nearest neighbor

Fermion action:

$$\begin{aligned} S_F \quad &= a^4 \sum_{x;\mu} \eta_\mu(x)\bar{\chi}(x)\frac{1}{2a}\left\{c_1\left[U_\mu(x)\chi(x+\mu) - U^\dagger(x-\mu)\chi(x-\mu)\right]\right. \\ &+c_2\left[U_\mu(x)U_\mu(x+\mu)U_\mu(x+2\mu)\chi(x+3\mu)\right. \\ &\left.\left.-U^\dagger_\mu(x-\mu)U^\dagger_\mu(x-2\mu)U^\dagger_\mu(x-3\mu)\chi(x-3\mu)\right]\right\} \\ &+a^4 m \sum_x \bar{\chi}(x)\chi(x) \end{aligned}$$

} Naik term 3rd-nn

We know that:

Hermiticity of the Transfer matrix is lost (complex energy eigenvalues)
When and how does it manifest?

Luscher, Weisz '84

A solvable model: (1d) Ising chain with n-n-n interactions (ANNNI models)

Arisue, Fujiwara '84

This case:

Naik term modifies the free fermion propagator

$$S_F(p)^{-1} = \sum_\mu i\gamma_\mu \left(\frac{9}{8}\sin p_\mu - \frac{1}{24}\sin 3p_\mu\right)$$

modified by strong coupling interactions
→ ghosts

Baryon number density

$$n(\mu) = d/d_\mu logZ(\mu) = n_1(\mu) + n_3(\mu)$$

$n(\mu = 0)$=0 in two ways: $\begin{cases} n_1 = n_3 = 0 \\ n_1 = -n_3 \neq 0 \end{cases}$

oscillatory component allowed in Goldstone channel
forward-backward asymmetry allowed

*Plausibly related to S_4 ($T=S_4^2$) investigated by Cheng, Hasenfratz, Schaich '12

Signatures

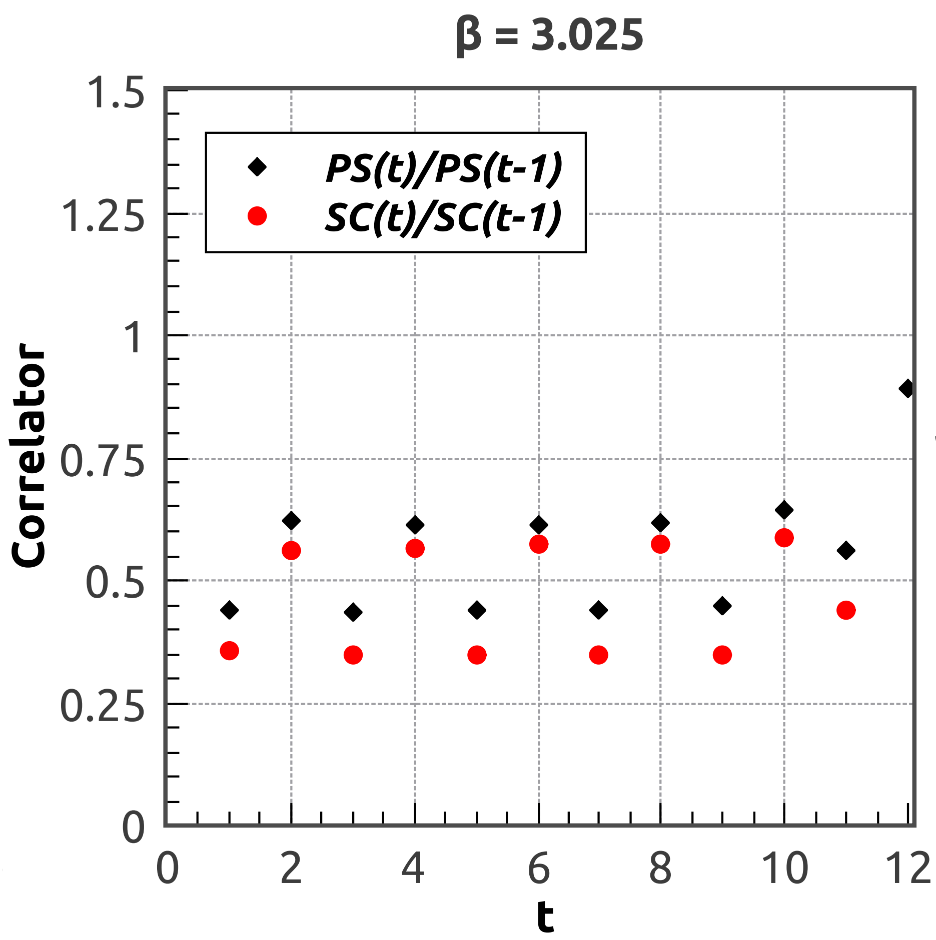
Propagators

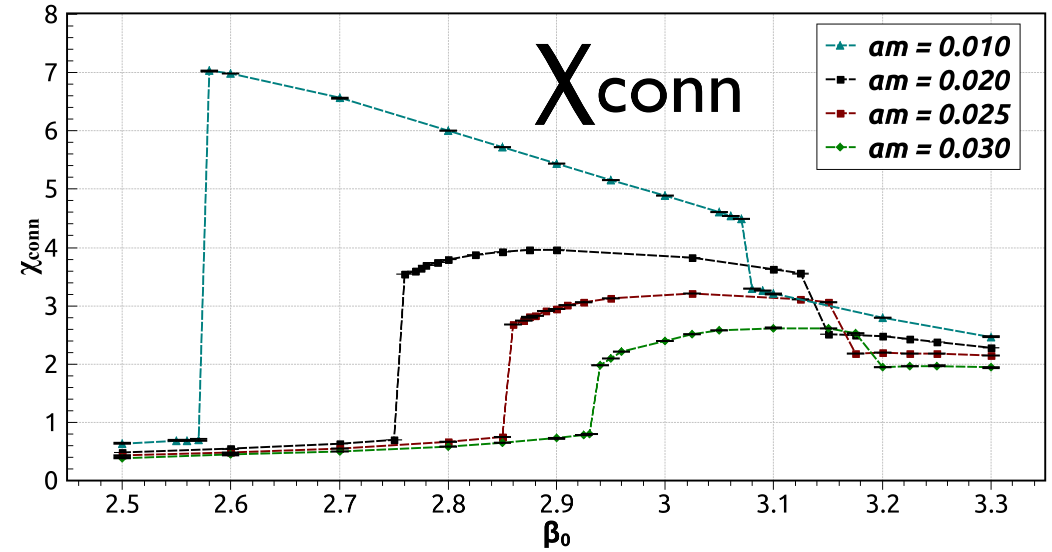
Susceptibilities

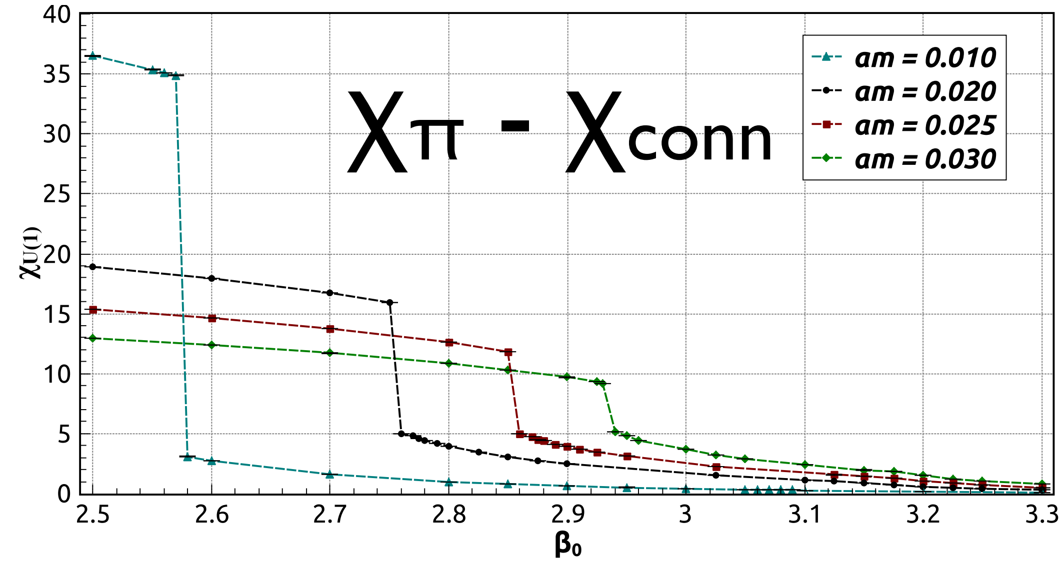
$$C_\pi(t)$$

$$\chi_\pi = \frac{\langle\bar{\psi}\psi\rangle}{m} = \int C_\pi(t)$$

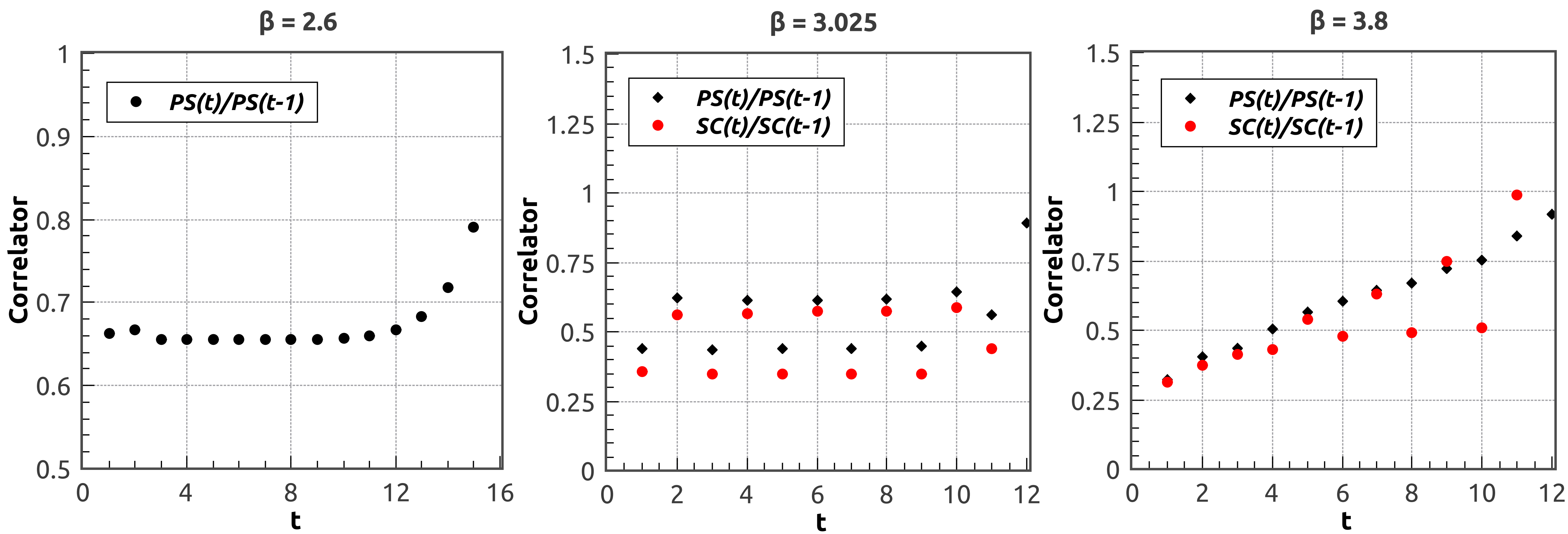
oscillation ⇒ discontinuity





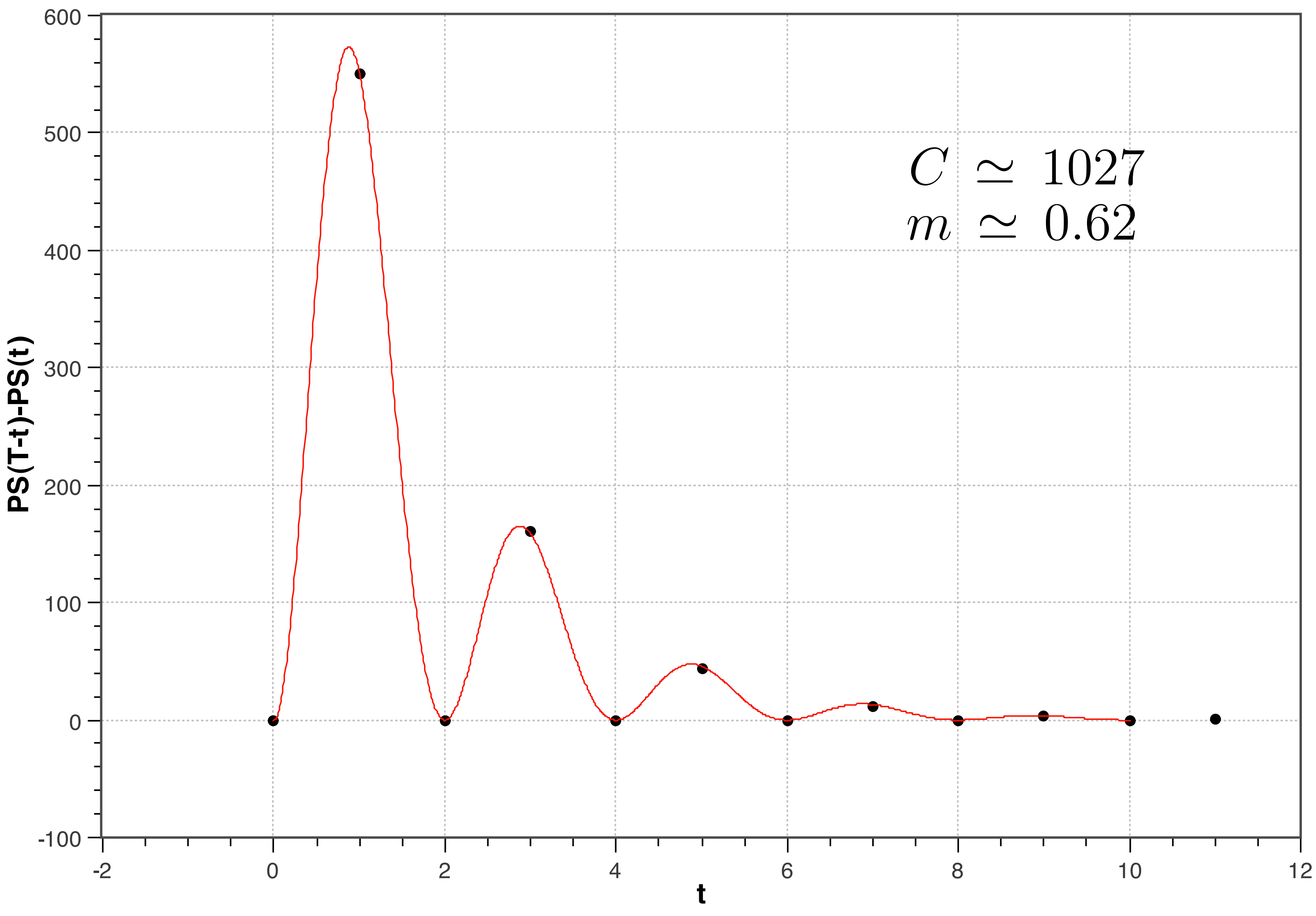


Degeneracy and chiral symmetry



The asymmetry

$$A \sim C\,\left(1-(-1)^t\right)\,\left(e^{-mt} - e^{-m(T-t)}\right)$$



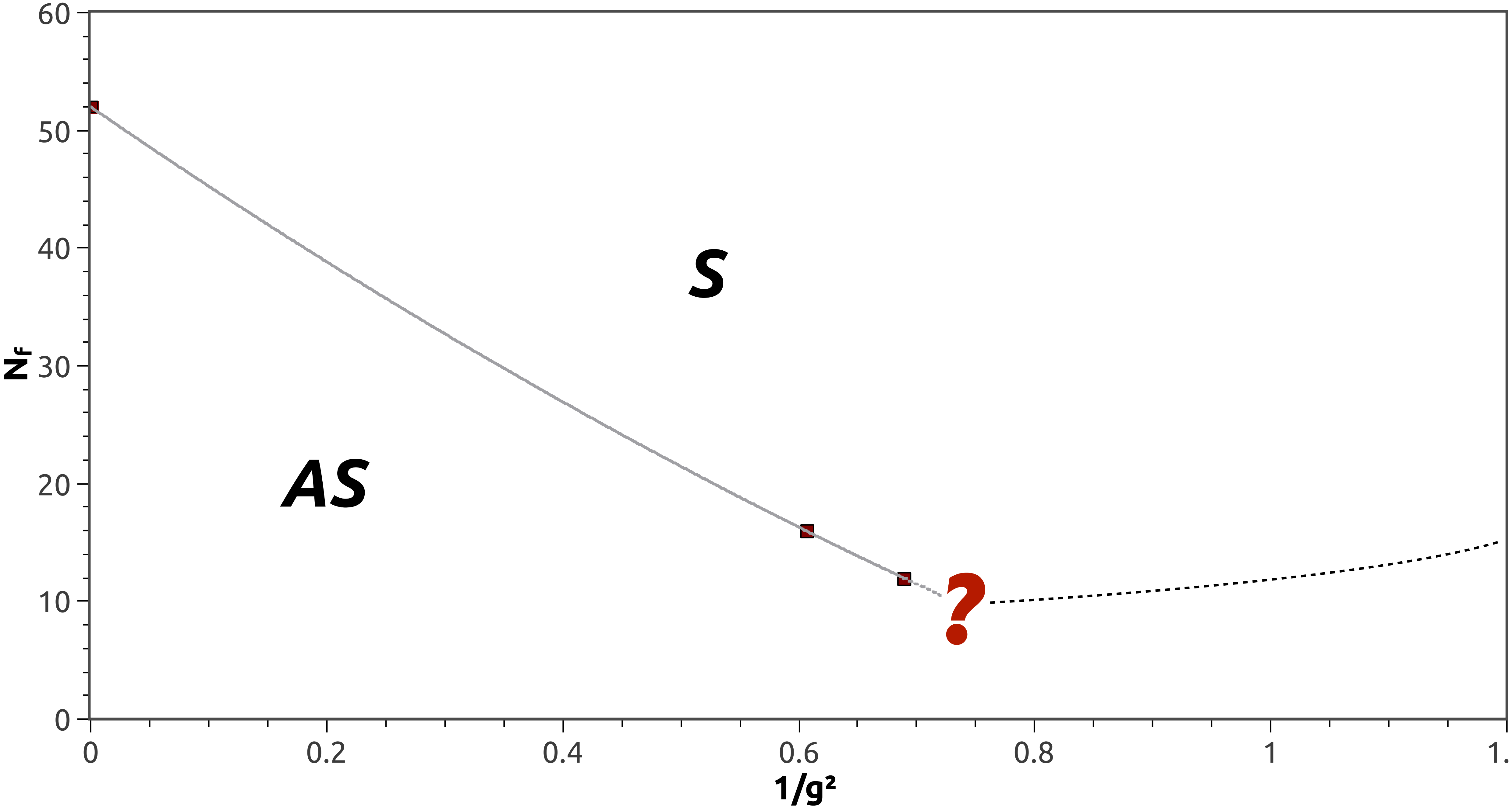
Remarks

Hermiticity loss of the transfer matrix (complex eigenvalues) is a general property of Symanzik improved gauge theories

We have found an example where the Naik improvement of the staggered fermion action generates a new phase of the system signalled by a discontinuity of the chiral susceptibility (change of mass slope of the chiral condensate)

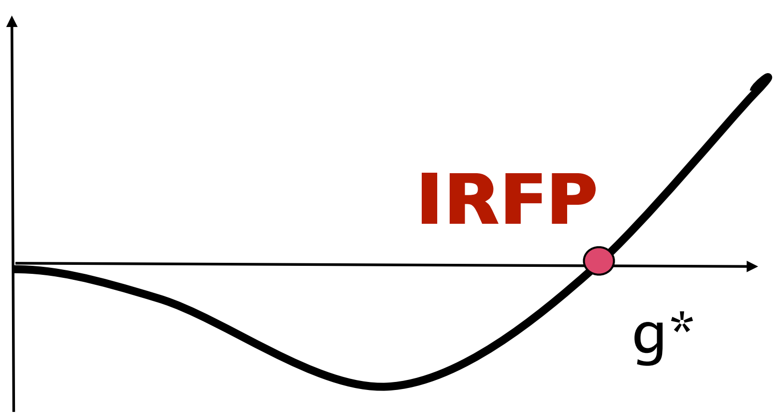
The same theoretical analysis is potentially useful for the lattice formulation of strongly coupled systems such a graphene.

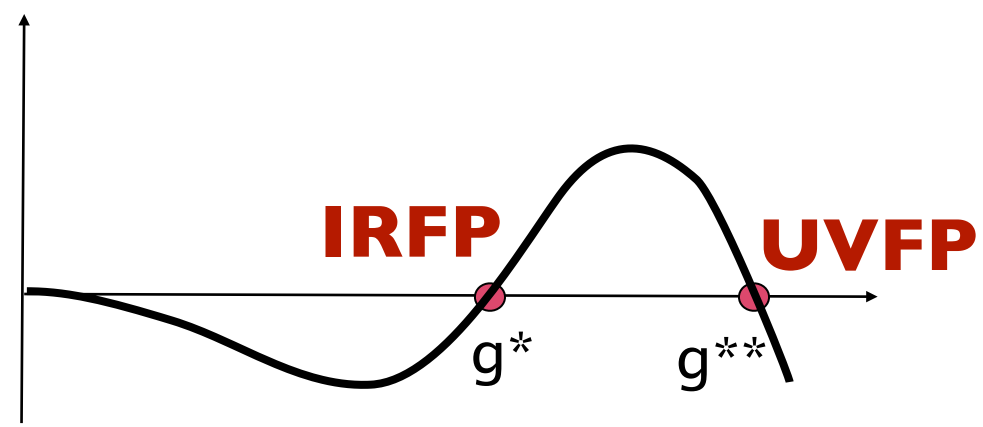
AdS/CFT
Disappearance of the CW



60
50
40
30
20
10
0
Nf
S
AS
?
0
0.2
0.4
0.6
0.8
1
1.2
1/g²

Which scenario is realized ?





SQCD: duality guarantees that the (electric) theory is infinitely strongly coupled below the CW

FP pair annihilation

see Kaplan et al '09

SQCD and QCD β-functions

A conformal window for SQCD exists in the region 3/2 $N_c < N_f < 3N_c$ — Seiberg '95

SQCD: $$\beta_g = -\frac{g^3}{16\pi^2}\,\frac{3N_c - N_f(1-\gamma_0)}{1-\frac{g^2 N_c}{8\pi^2}}$$ — NSVZ '83 '86

QCD?: Large N limit

≠ SYM

$$\beta(g_c) = \frac{-\beta_0^\infty g_c^3 + \frac{\beta_j}{4} g_c^3 \left(\frac{\partial \log Z}{\partial \log \Lambda} + c_F \frac{g_c^2}{16\pi^2}\right) + c_F \frac{g_c^3}{16\pi^2}\left(1+\gamma(g_c^2)/2\right)}{1-\beta_j g_c^2}$$

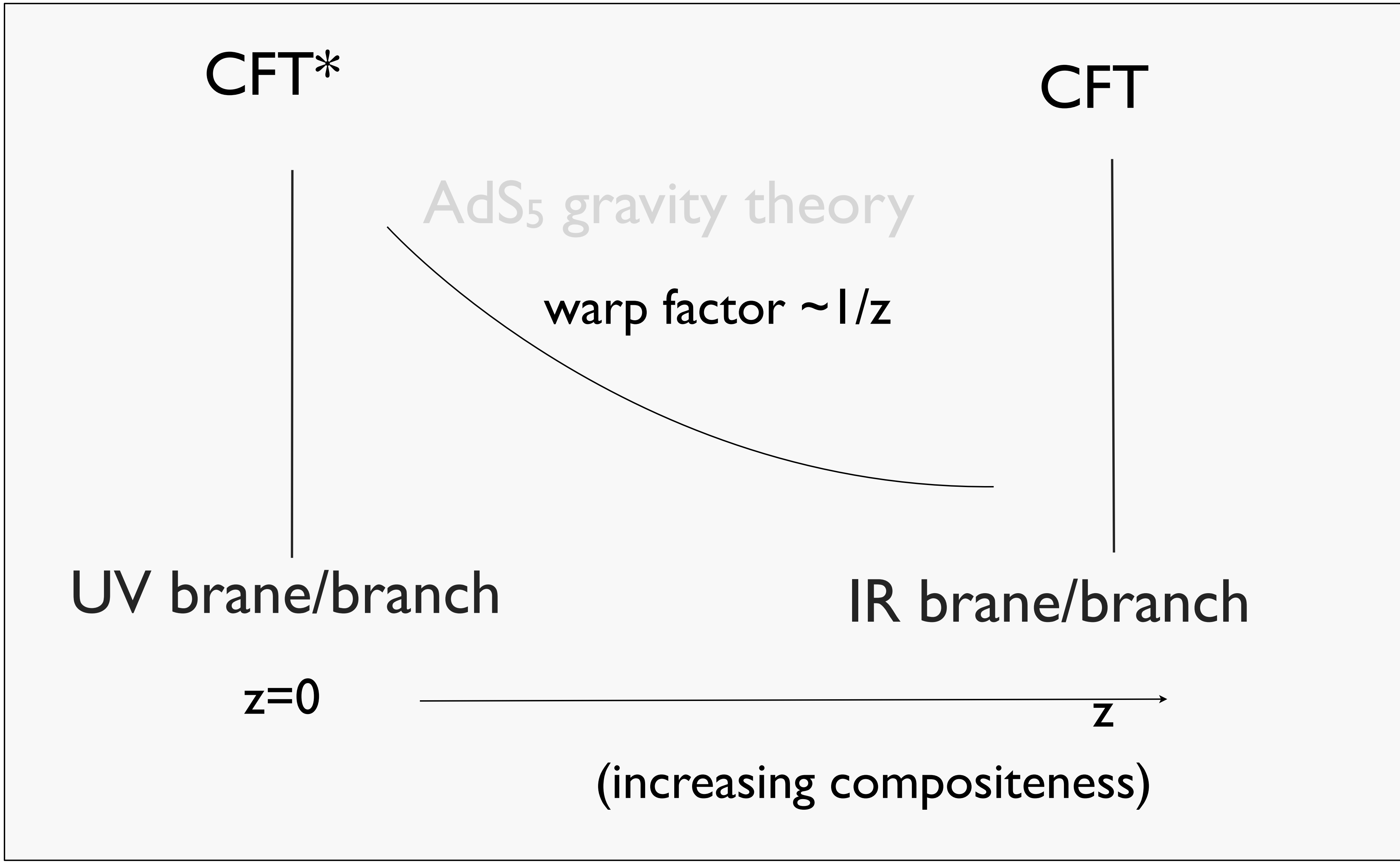
Reproduces 2-loop beta in the (perturbative) Veneziano limit

Caveat: ∃ IRFP also for Nf=0 - g* is RG scheme dependent

YM: Bochicchio '08
(EP '09)

see also Brodsky, Schrock '08

AdS/CFT



"IR/UV correspondence"

$z \to 0$ IR gravity

$z \to 0$ UV field theory

An example of FP merging in "modified" SQCD

Large N_f, N_c: N_f/N_c fixed - SUGRA backgrounds

Maldacena, Nunez '04
Casero Nunez Paredes '08
Conte Gaillard Ramallo '11

$\Downarrow$

SQCD + quartic operators

Barranco EP Russo '11

$N_f < 2N_c$ UV limit: $\beta \rightarrow \beta_{\rm NSVZ}(\gamma_0 = -1/2)$
IR limit: ordinary confinement

$N_f = 2N_c$ UVFP at strong coupling

$N_f > 2N_c$ Seiberg dual ($N_c \rightarrow N_f - N_c$, $N_f - 2N_c$ flips sign)

Summary

Conformal symmetry might play a role in particle physics at or well above the EWSB scale.

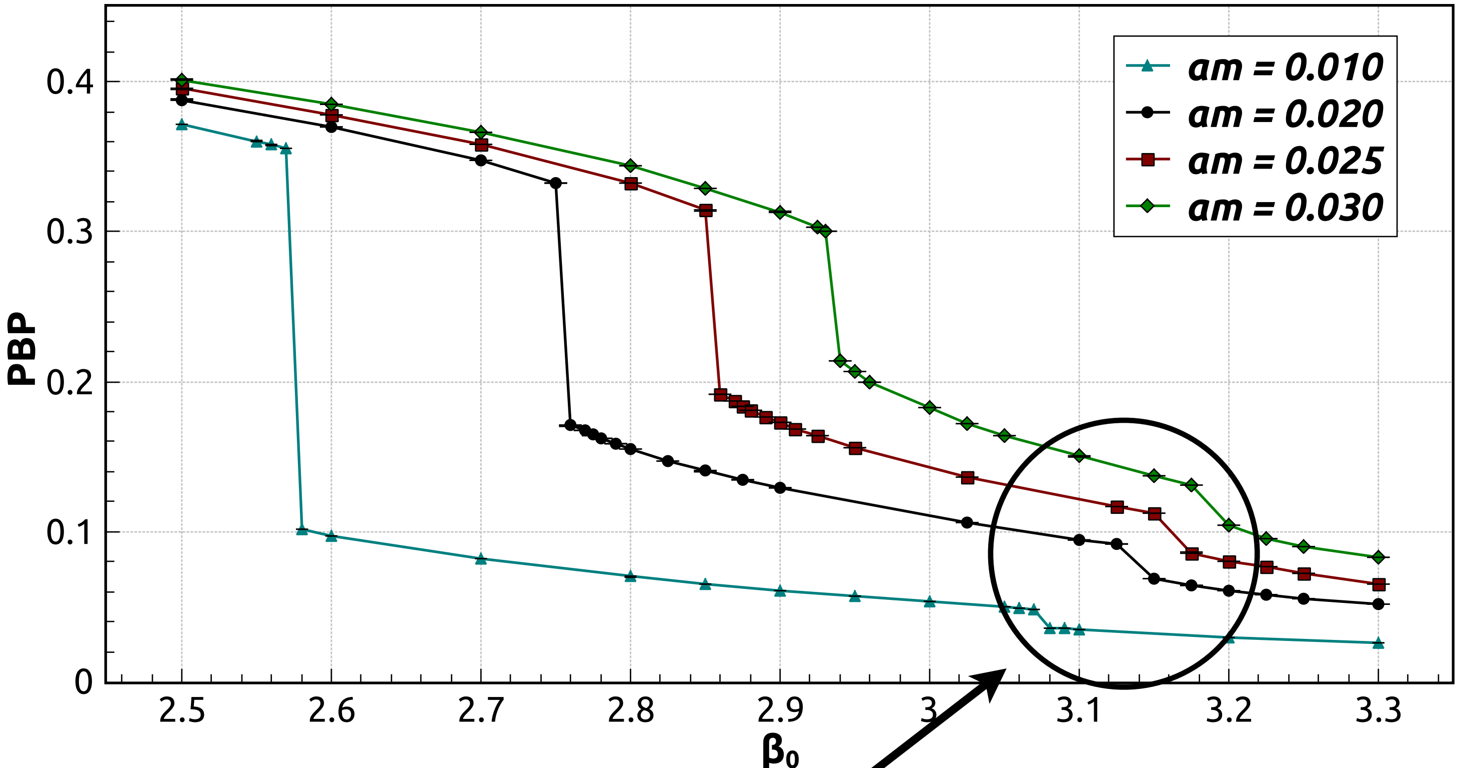
Large-Nf QCD is an instructive theory playground

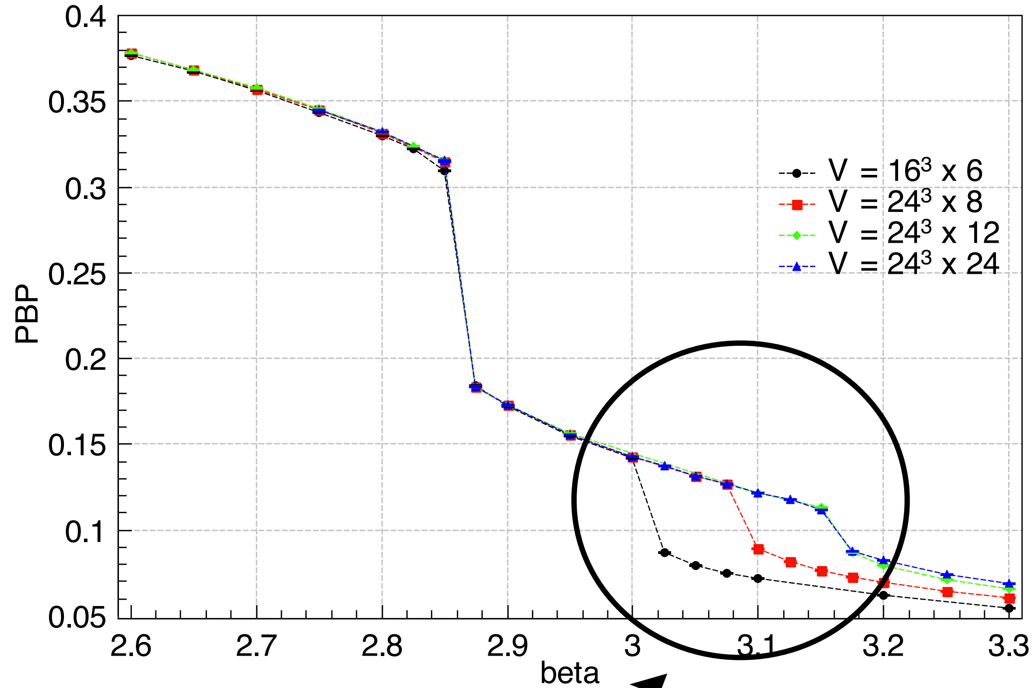
✓ The conformal window opens at around $N_f \sim 12$
✓ The spectrum and the physics of phase transitions provide distinctive signatures of (pre)conformality
✓ A preliminary study shows a change of trend of Tc for $N_f > 6$

Symanzik Improvement in strongly coupled systems can generate new phases. The same considerations apply to non-abelian gauge theories in the conformal window as well as systems such as graphene.

AdS/CFT is in its infancy, but useful and insightful tool, when trying to make connection with SQCD or QCD.

The bulk transition(s)

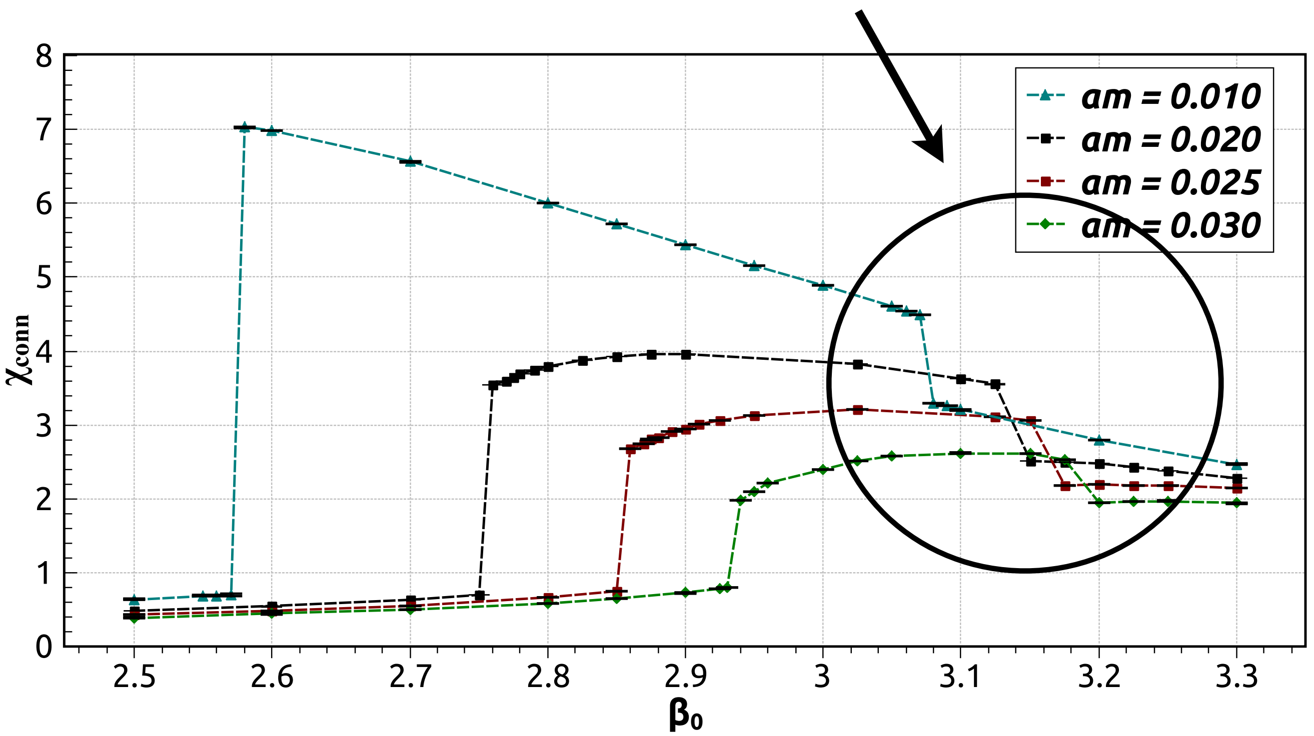


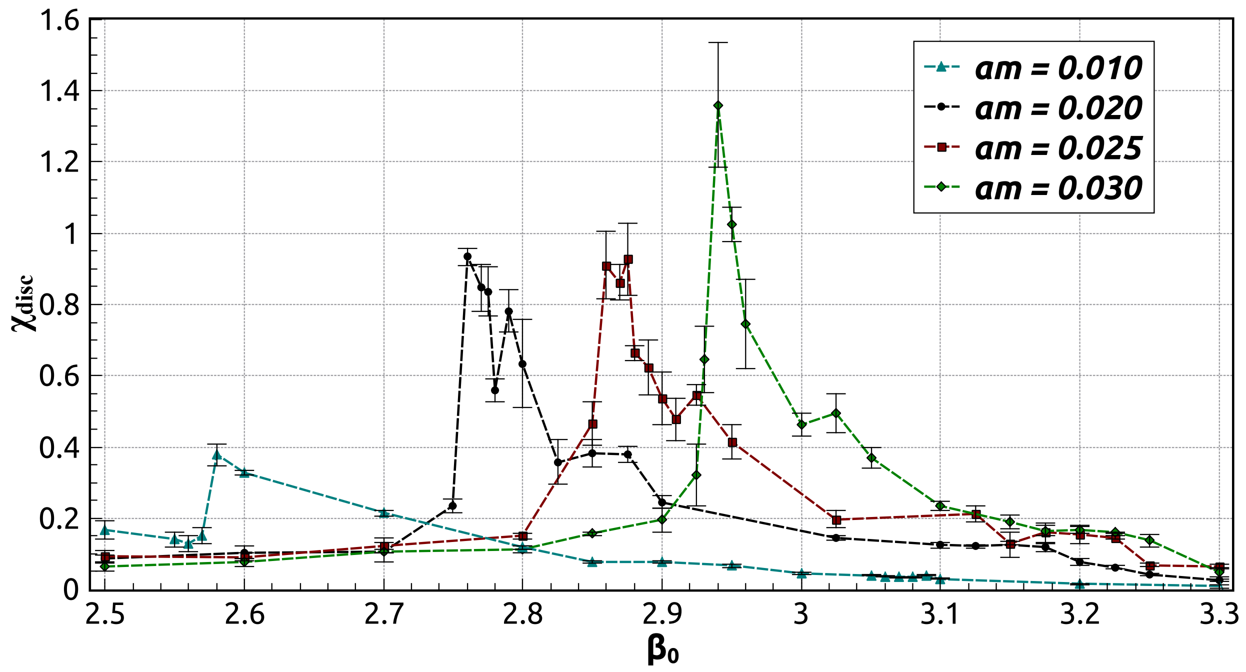


does not increase
with m decreasing

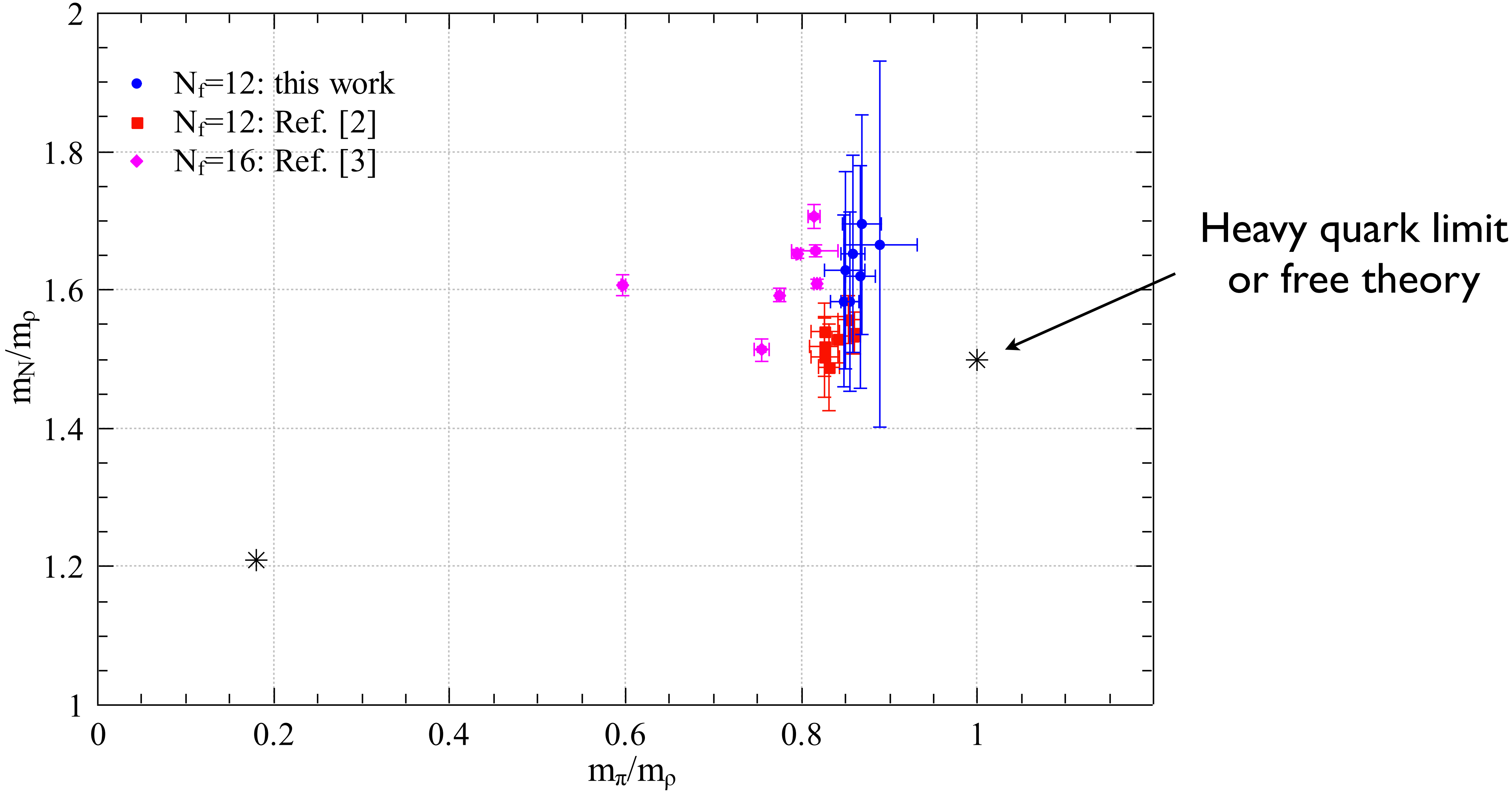
N_t dependence only for $N_t \leq 12$

Chiral susceptibilities
mass dependence





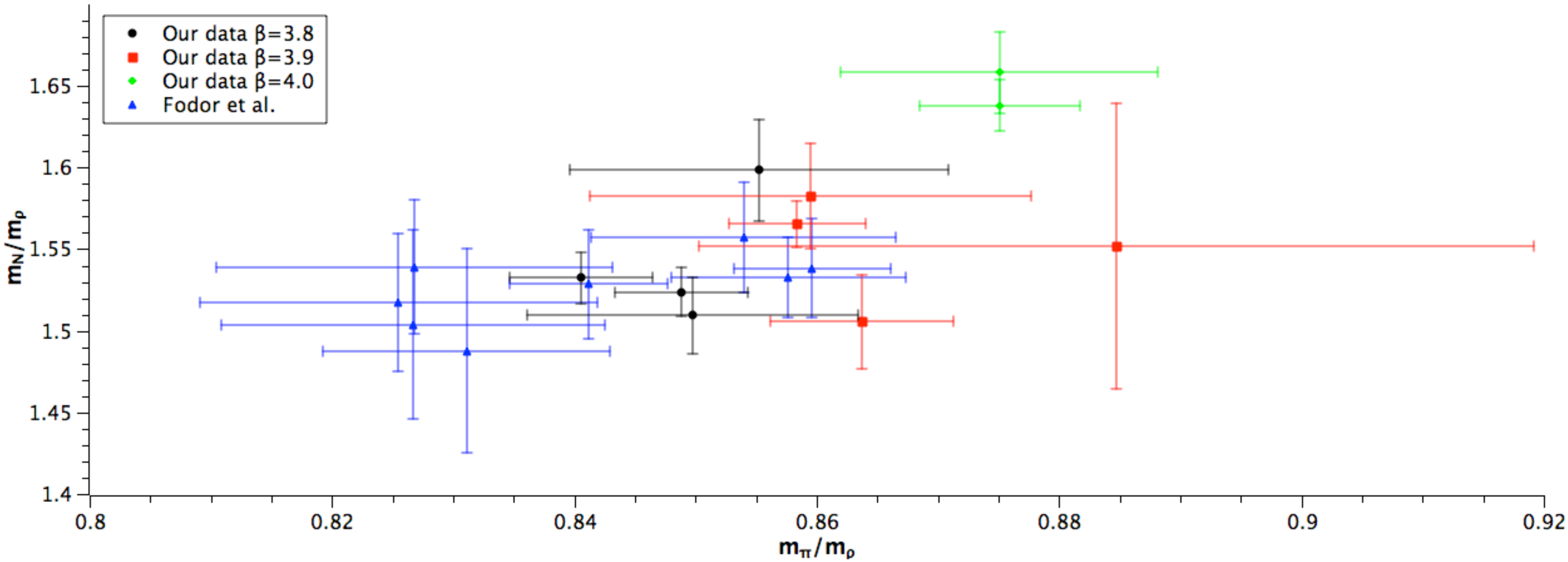
The Edinburgh Plot of Nf=12 and Nf=16



Bare quark masses span a range 0.01 to 0.07 at various β for Nf=12
Bare quark masses span a range 0.025 to 0.15 at various β for Nf=16

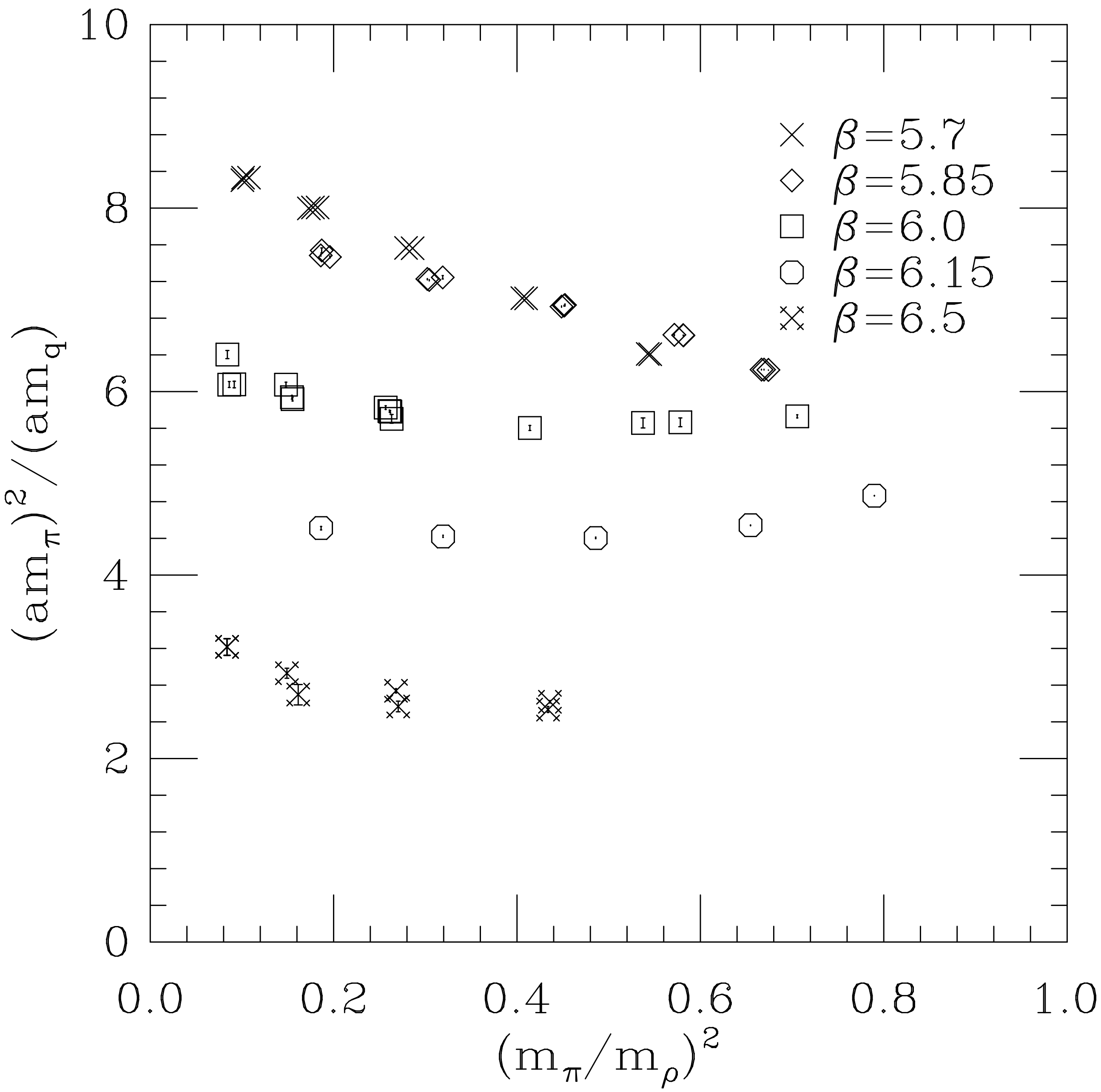
Damgaard, Heller, Krasnitz, Olesen 1997
Fodor, Holland, Kuti, Nogradi, Schroeder 2011

Zoom in at Nf=12



Data cover the same dynamical region

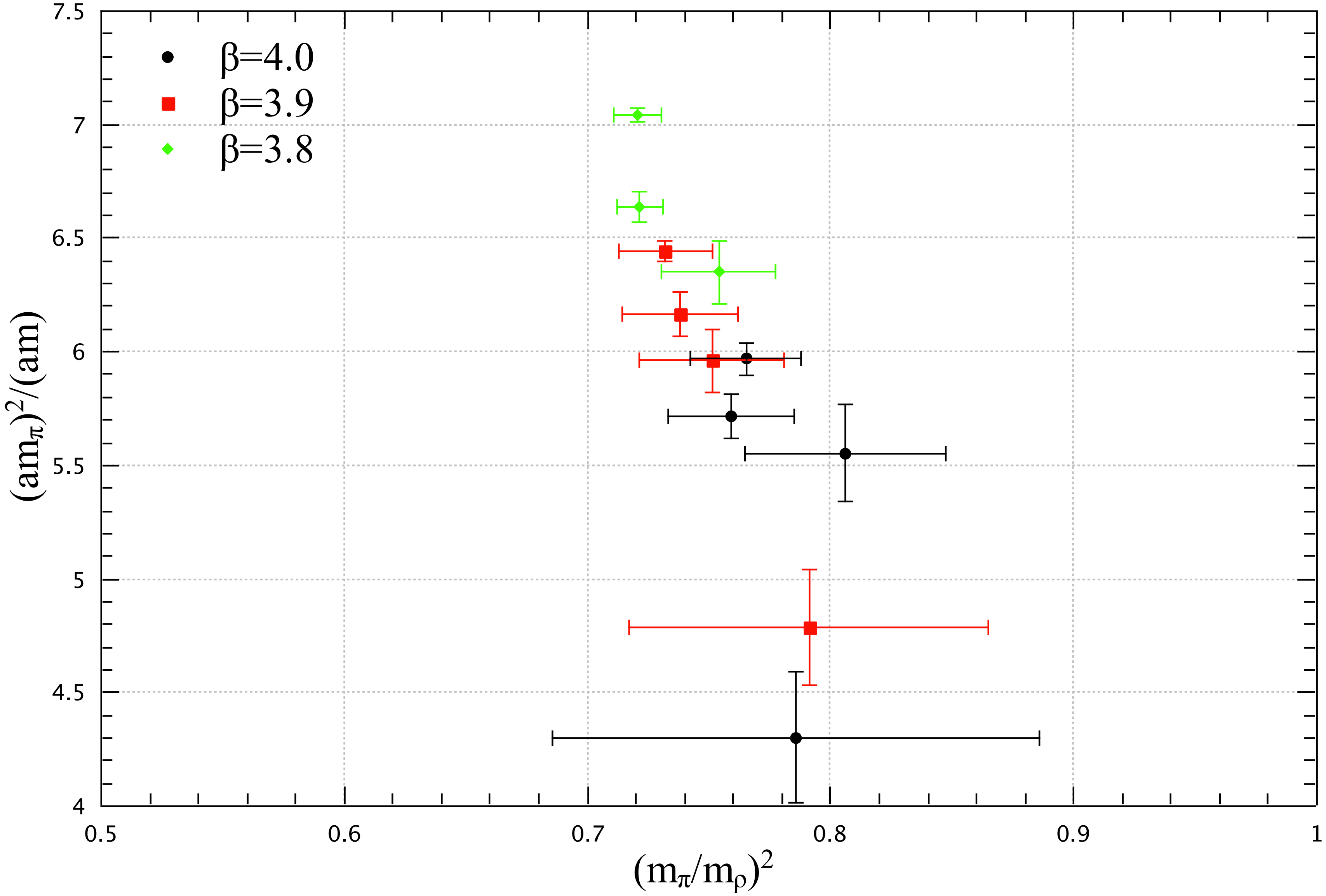
QCD



↑ Ratio increases

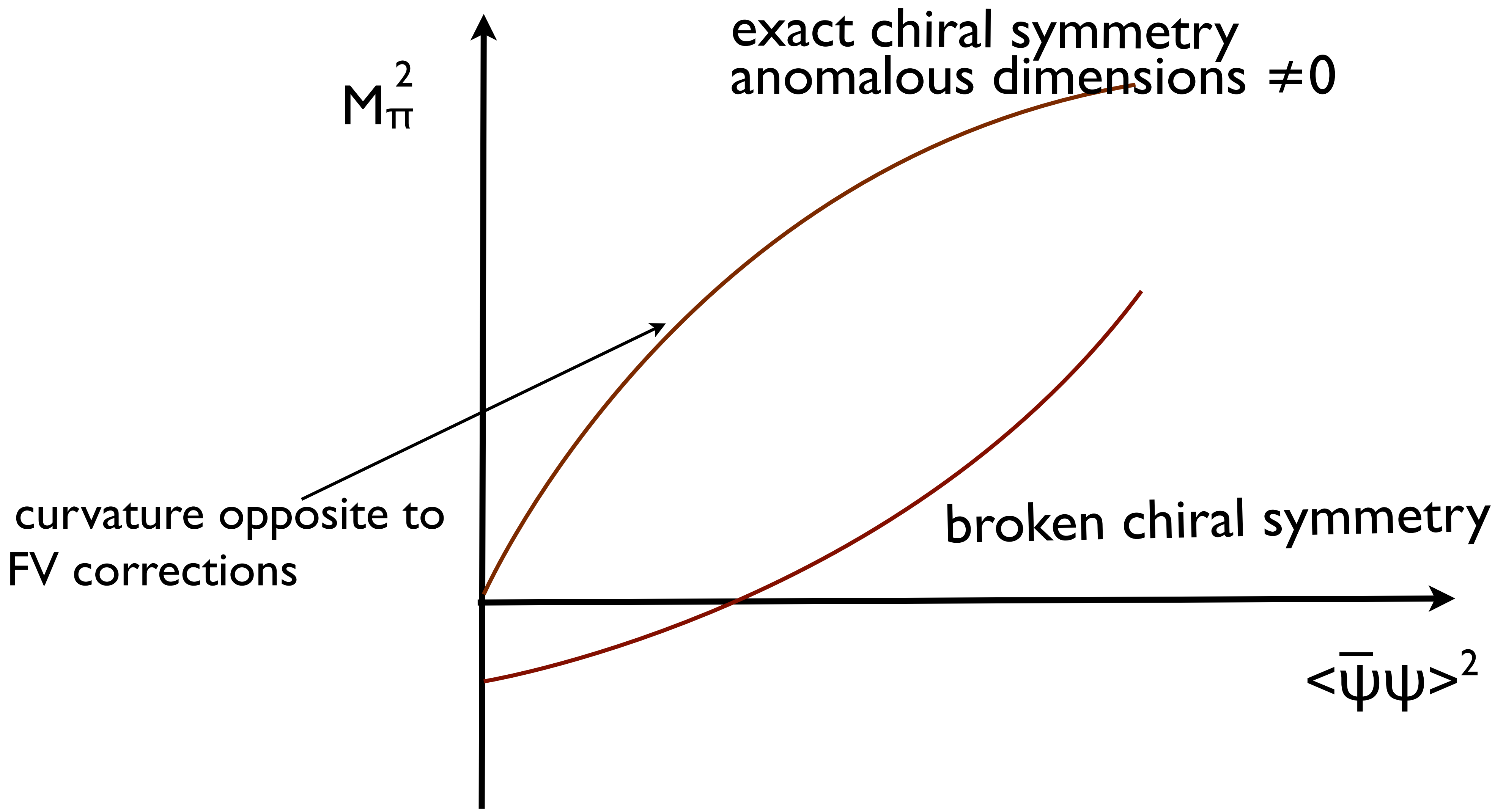
This is compatible with a negative β function

and non-QCD



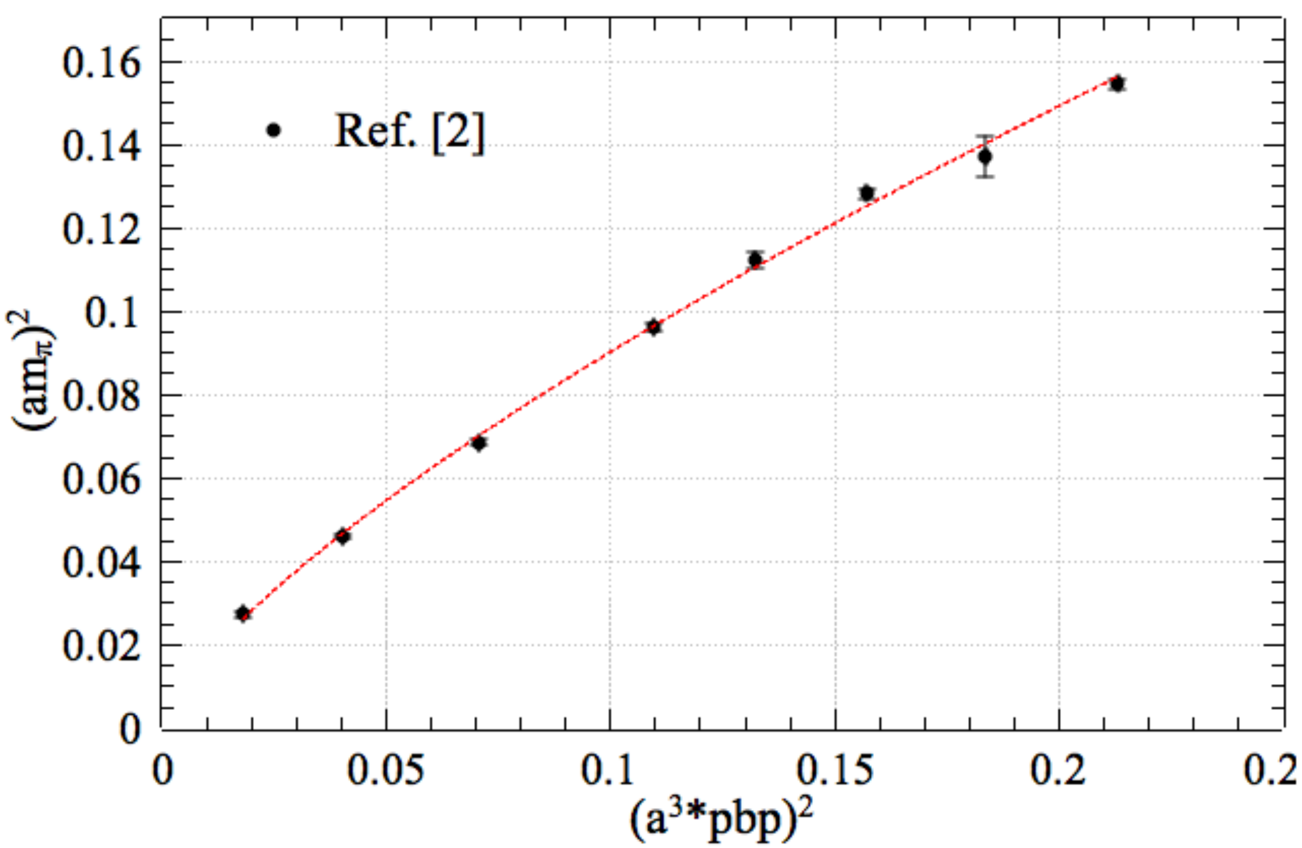
For a fixed m_π/m_ρ the inverted behavior with β_L is compatible with a positive β function

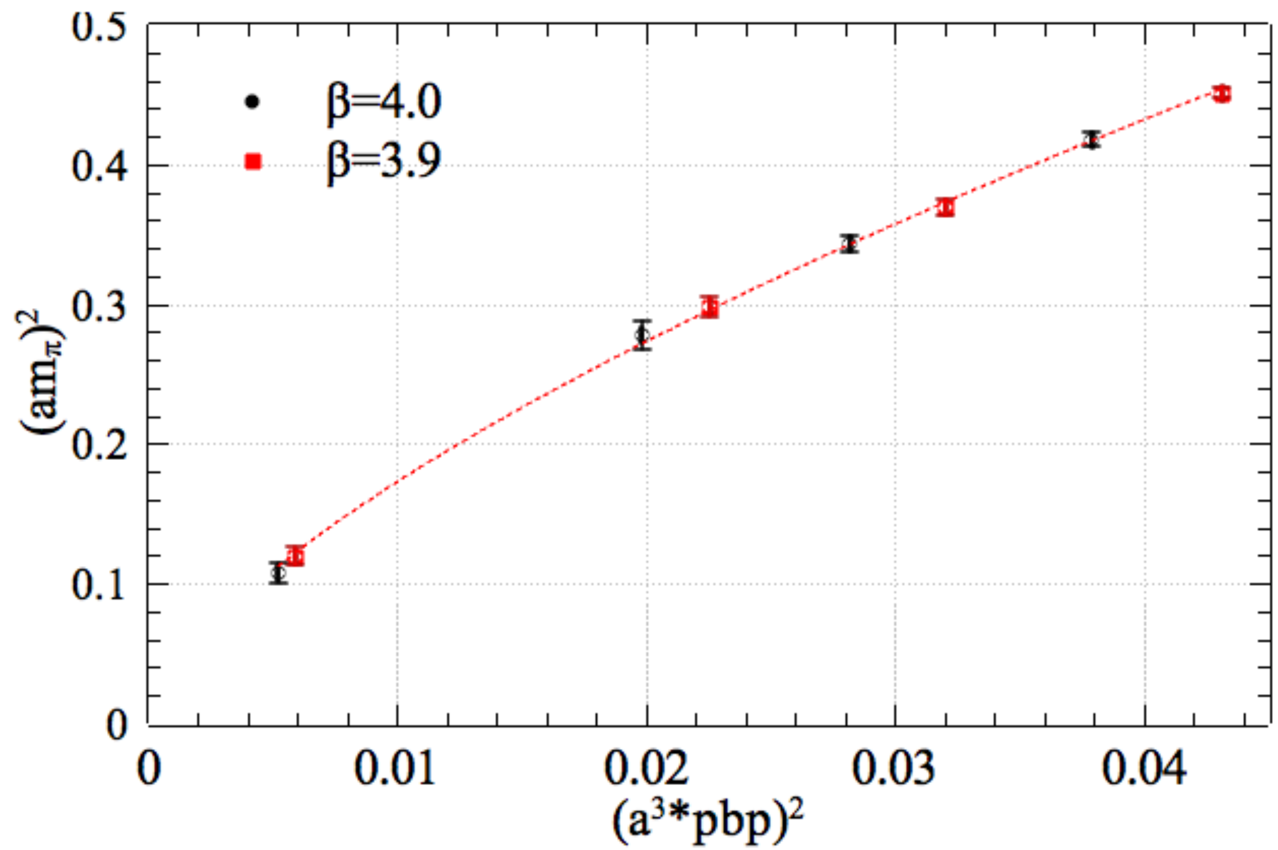
Pseudo Goldstone mass and chiral condensate



Kocic Kogut Lombardo 1993

Nf=12: lattice data





Exact chiral symmetry with non zero anomalous dimensions