Emergent Conformality in Gauge Theory

Elisabetta Pallante
University of Groningen

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

rijksuniversiteit groningen
FOM
NCF sara IBM

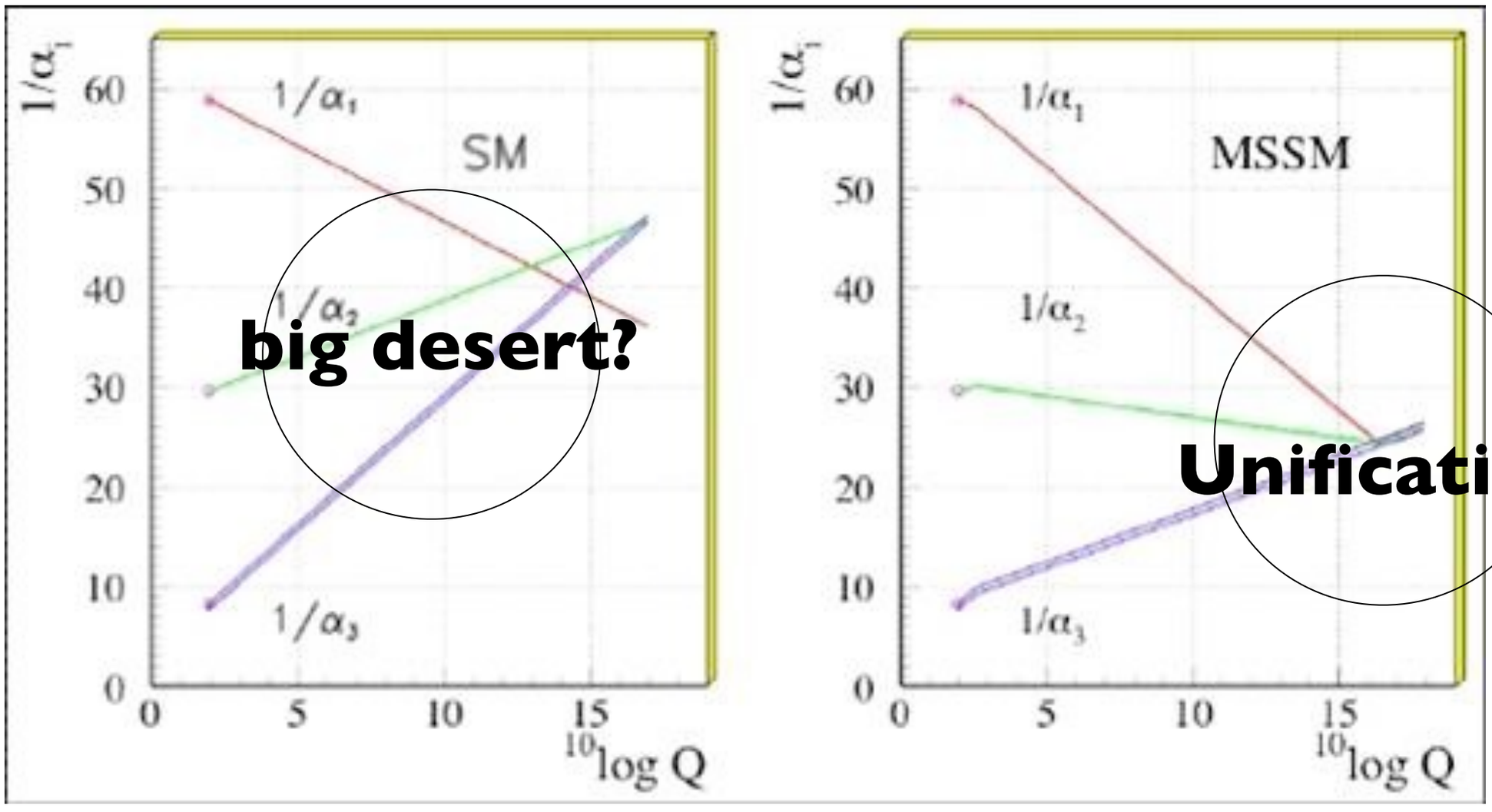
Outline

The role of conformal symmetry

The Phase Diagram of non Abelian gauge theories

Preconformal and Conformal dynamics

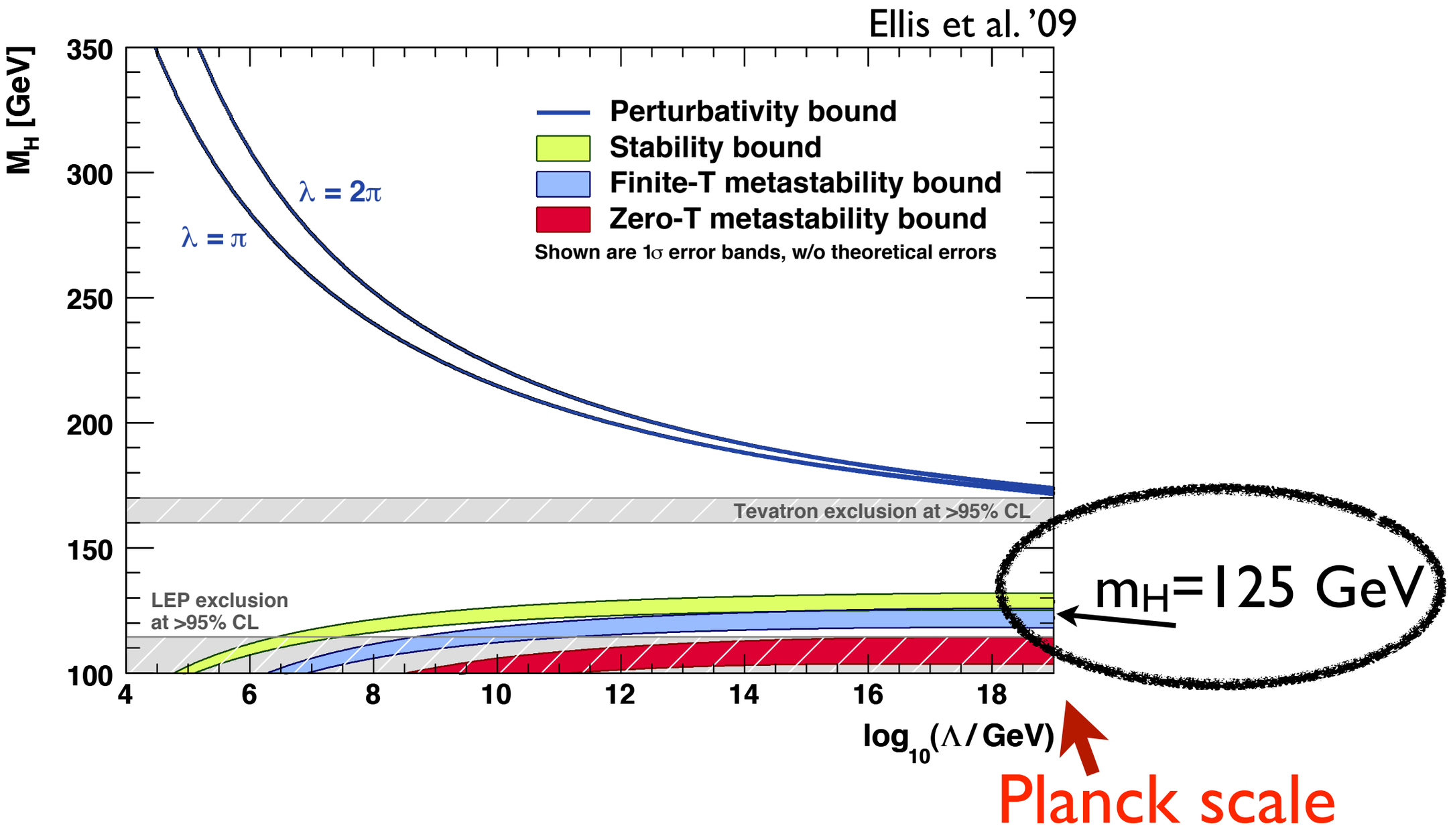
Disappearance of conformality with AdS/CFT



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

⇒ triviality and radiative corrections Cortese Petronzio EP '92

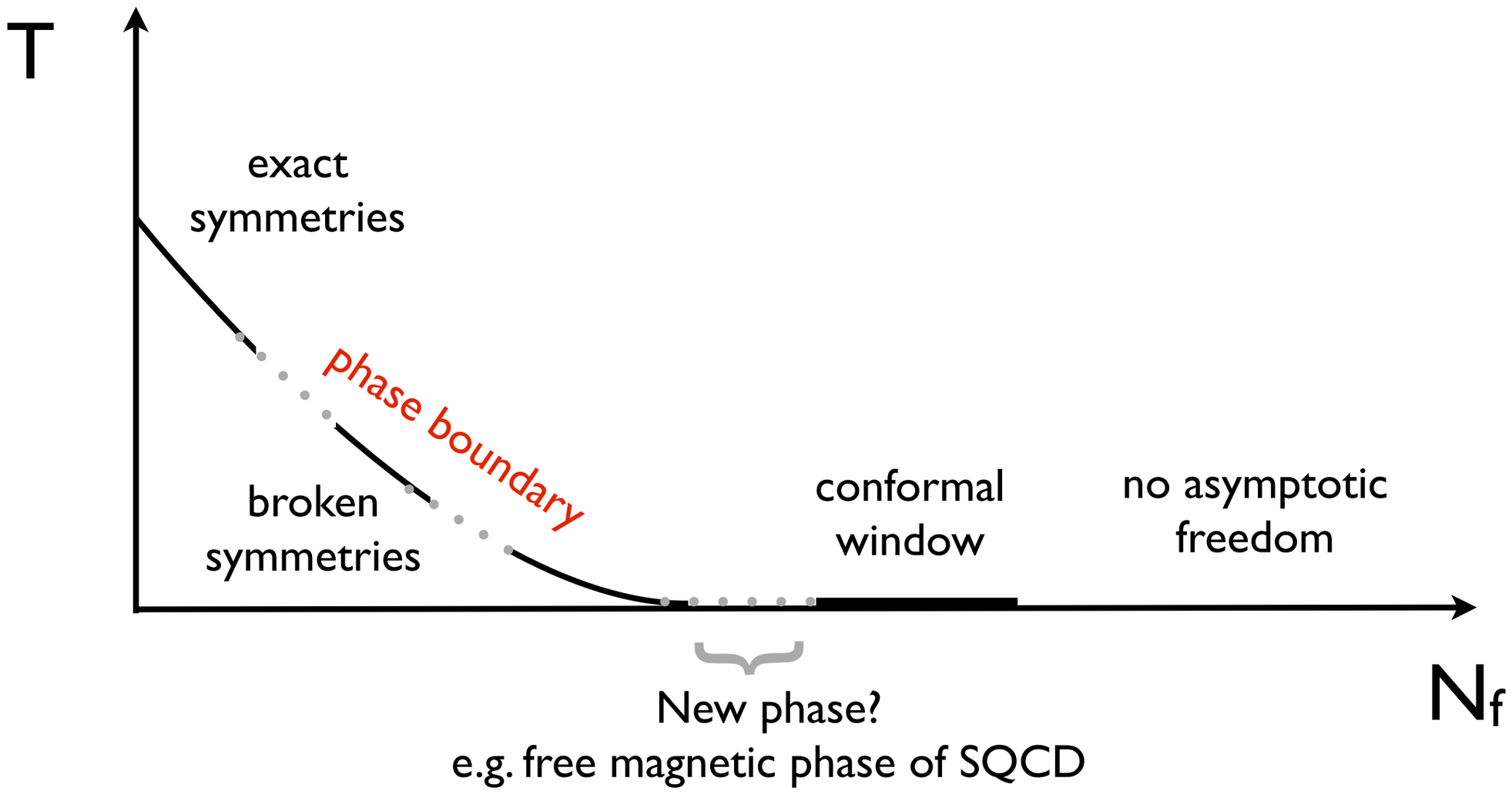
⇒ vacuum stability Isidori Ridolfi Strumia '01



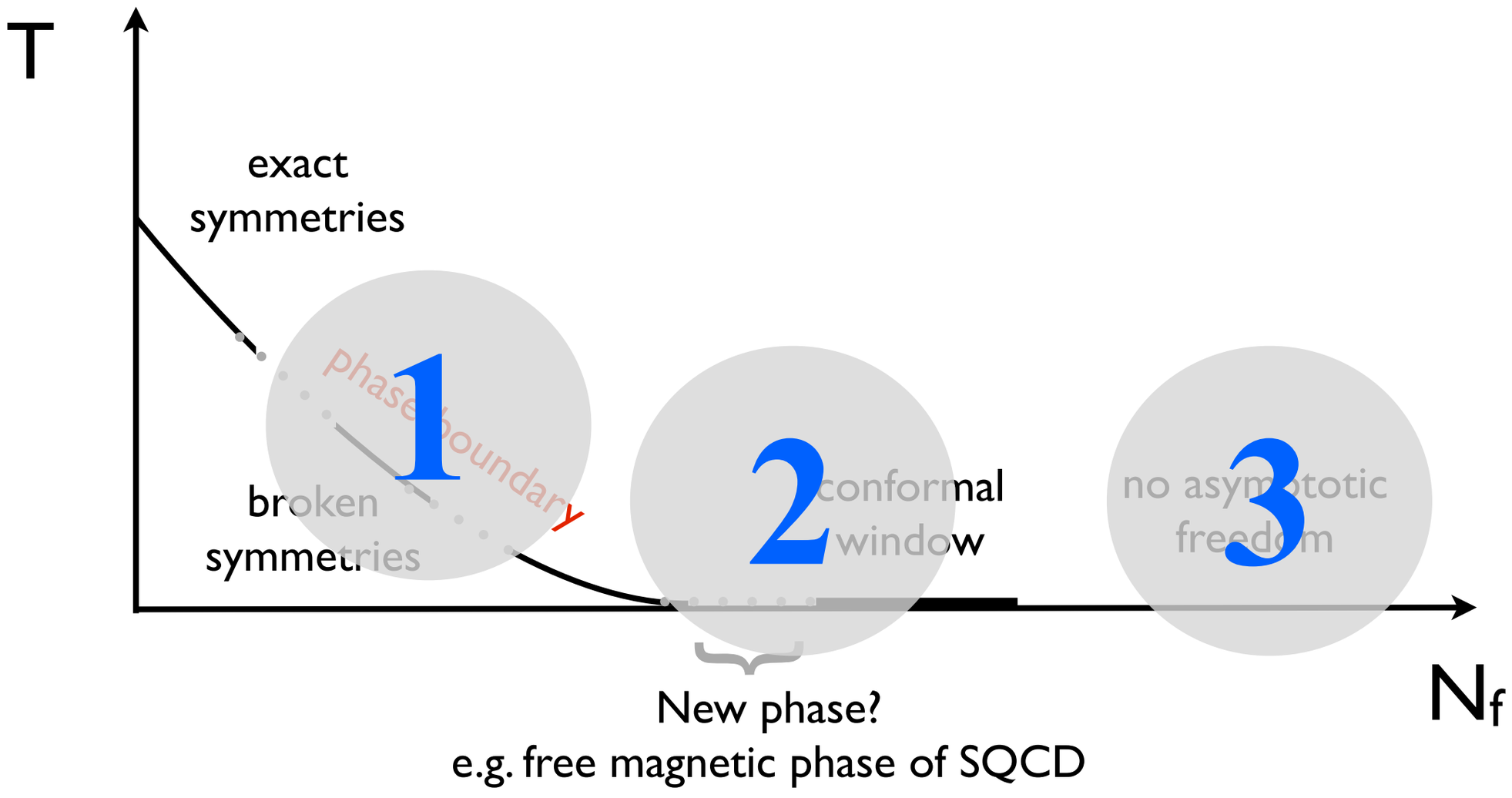
The SM may be a valid EFT up to the Planck scale

The Phase Diagram

Features and open questions



Features and open questions



1

What symmetries determine the phase boundary?
What is the relative role of confinement and chiral symmetry?

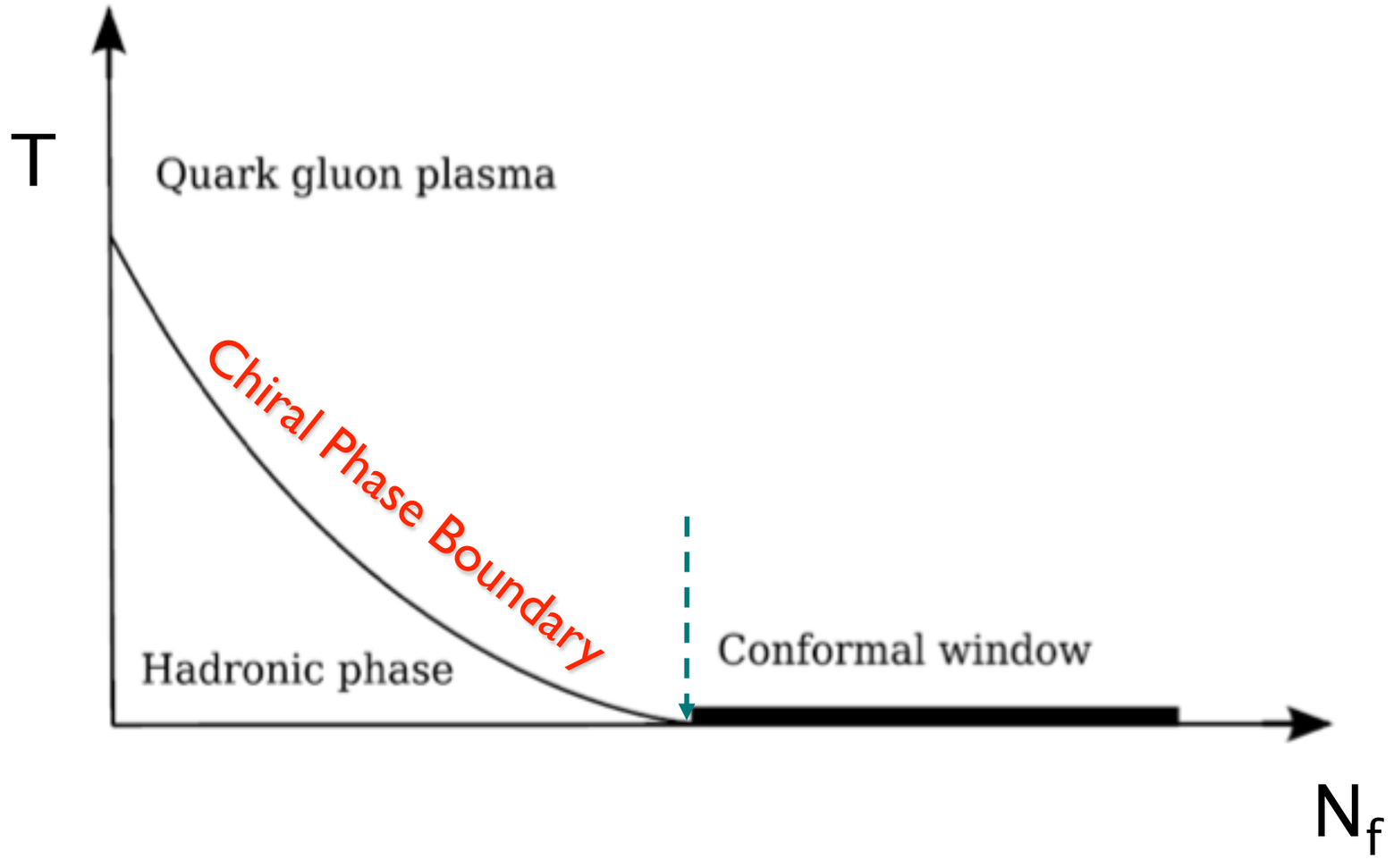
2

Is there a preconformal dynamics?
What are its signatures?
What is the mechanism (phase transition) that opens the conformal window?
Are there UVFP at strong coupling in addition to IRFP ?

3

Are there UVFP at strong coupling?

QCD: fundamental fermions



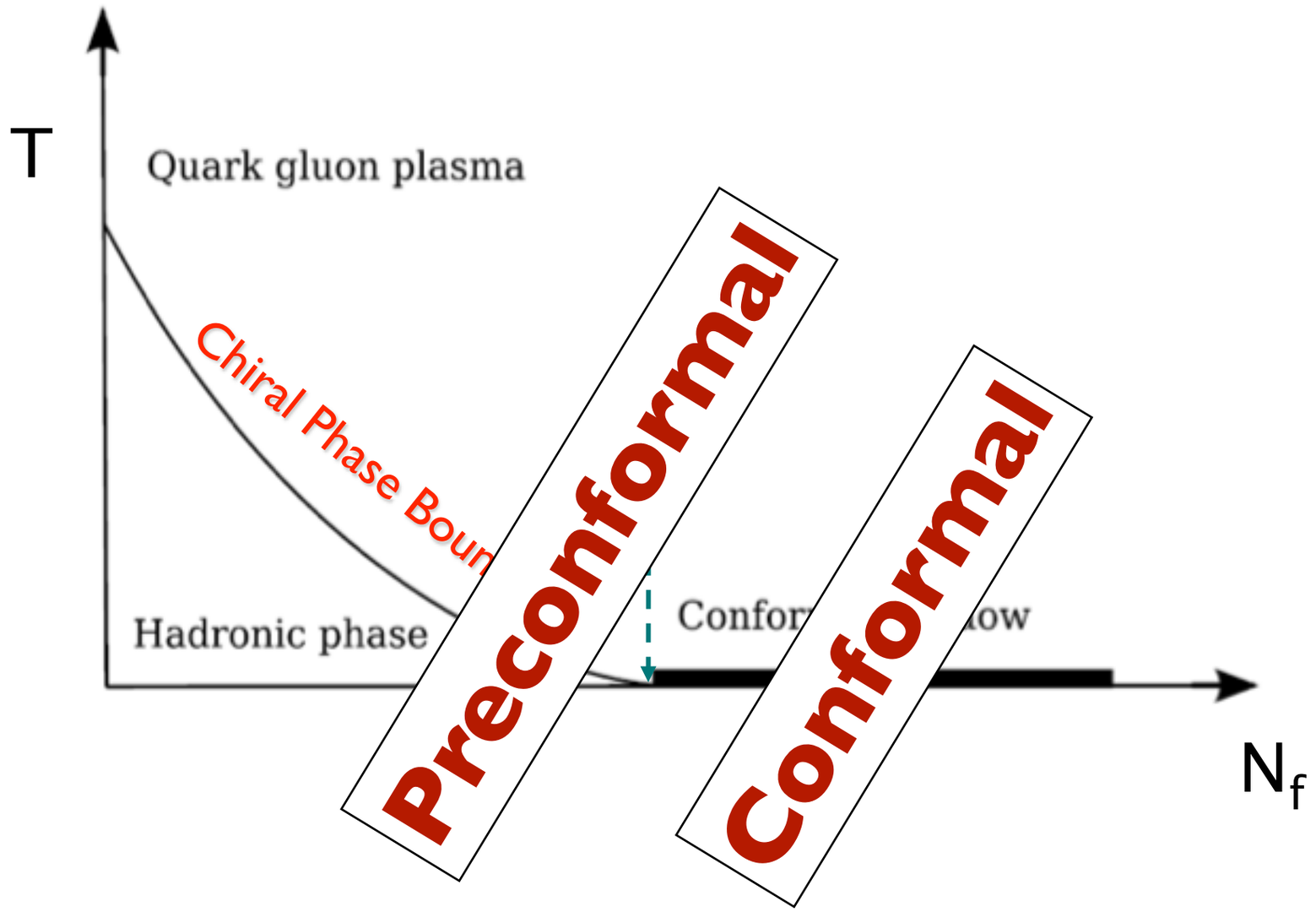
Physics of:

✓quark gluon plasma (QGP): high T - low Nf

✓preconformal regime (T=0, low T - high Nf)

✓conformal regime (T=0)

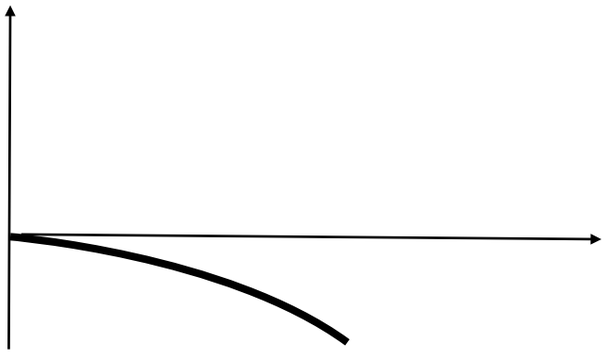
QCD: fundamental fermions



Beta functions

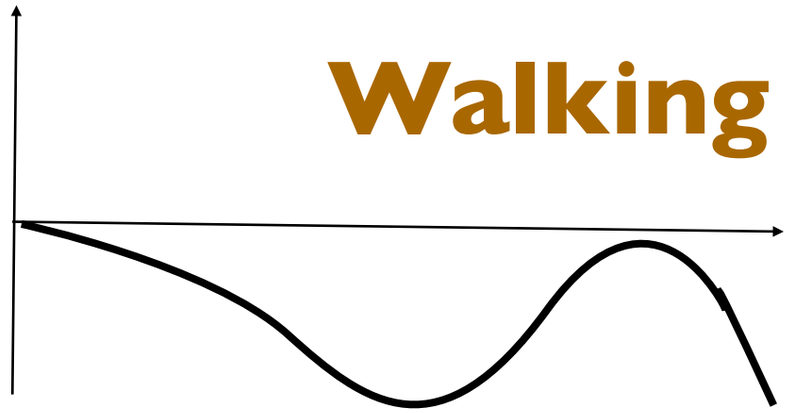
$\beta(g)$

$N_f < N_f^c$

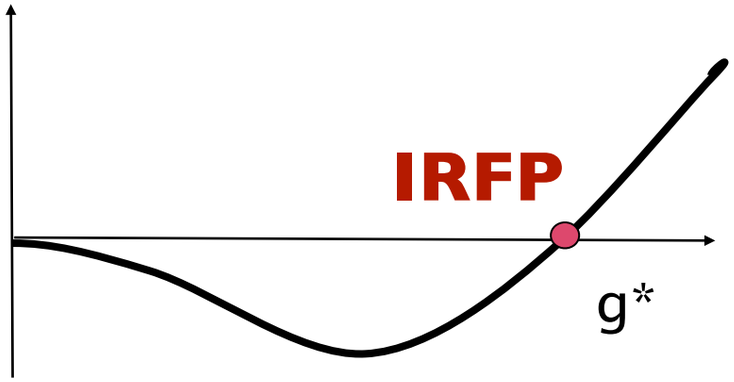


$N_f \lesssim N_f^c$

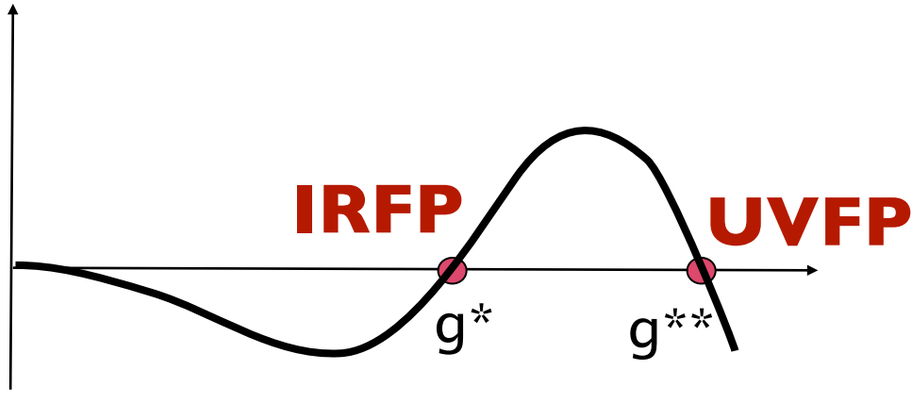
Walking ?



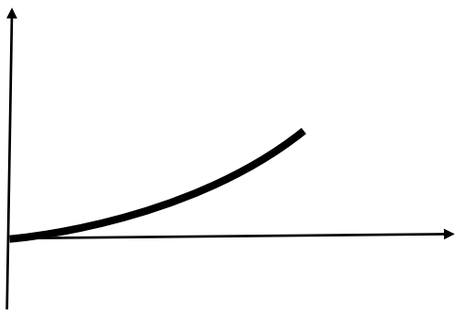
$N_f^{AF} > N_f > N_f^c$



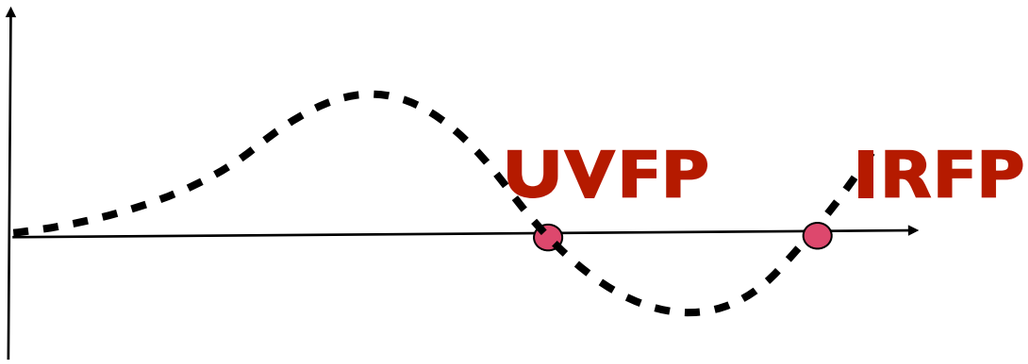
or



$N_f > N_f^{AF}$

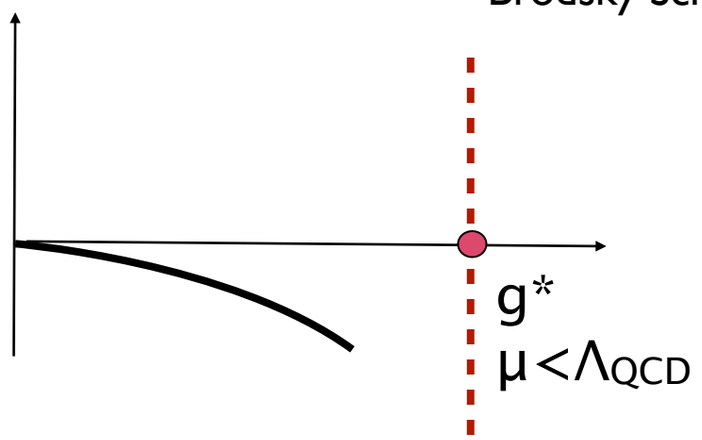


or



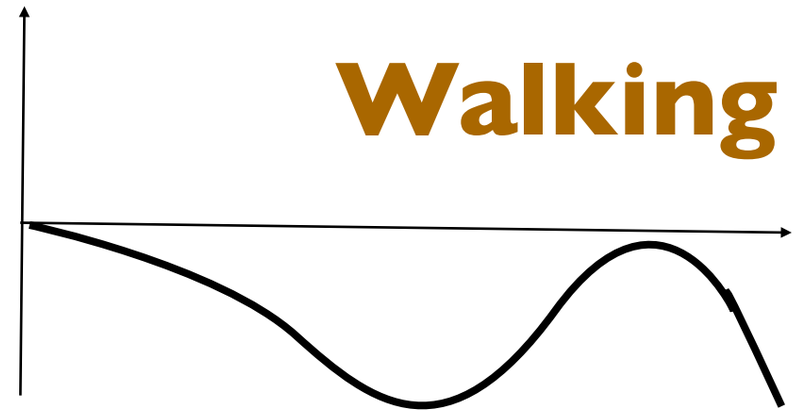
Brodsky Schrock '08

$N_f < N_f^c$

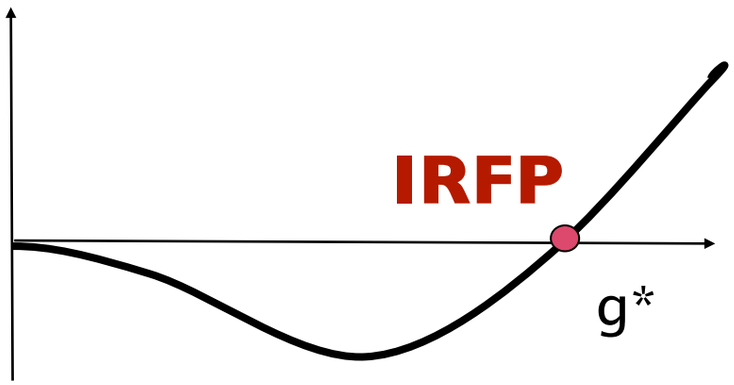


$N_f \lesssim N_f^c$

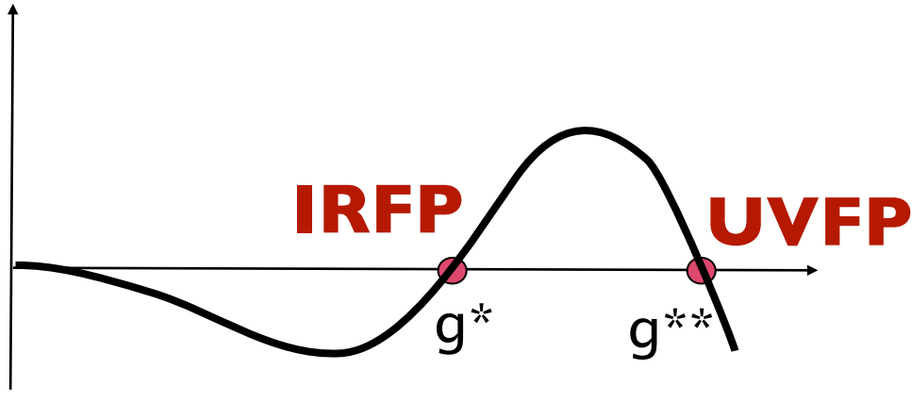
Walking ?



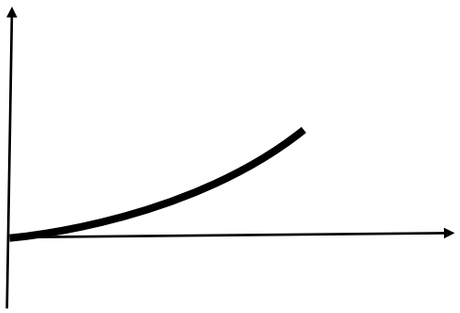
$N_f^{AF} > N_f > N_f^c$



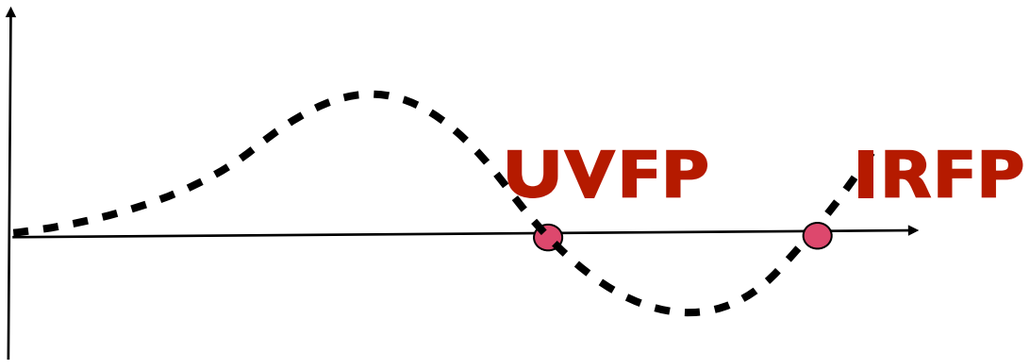
or



$N_f > N_f^{AF}$



or



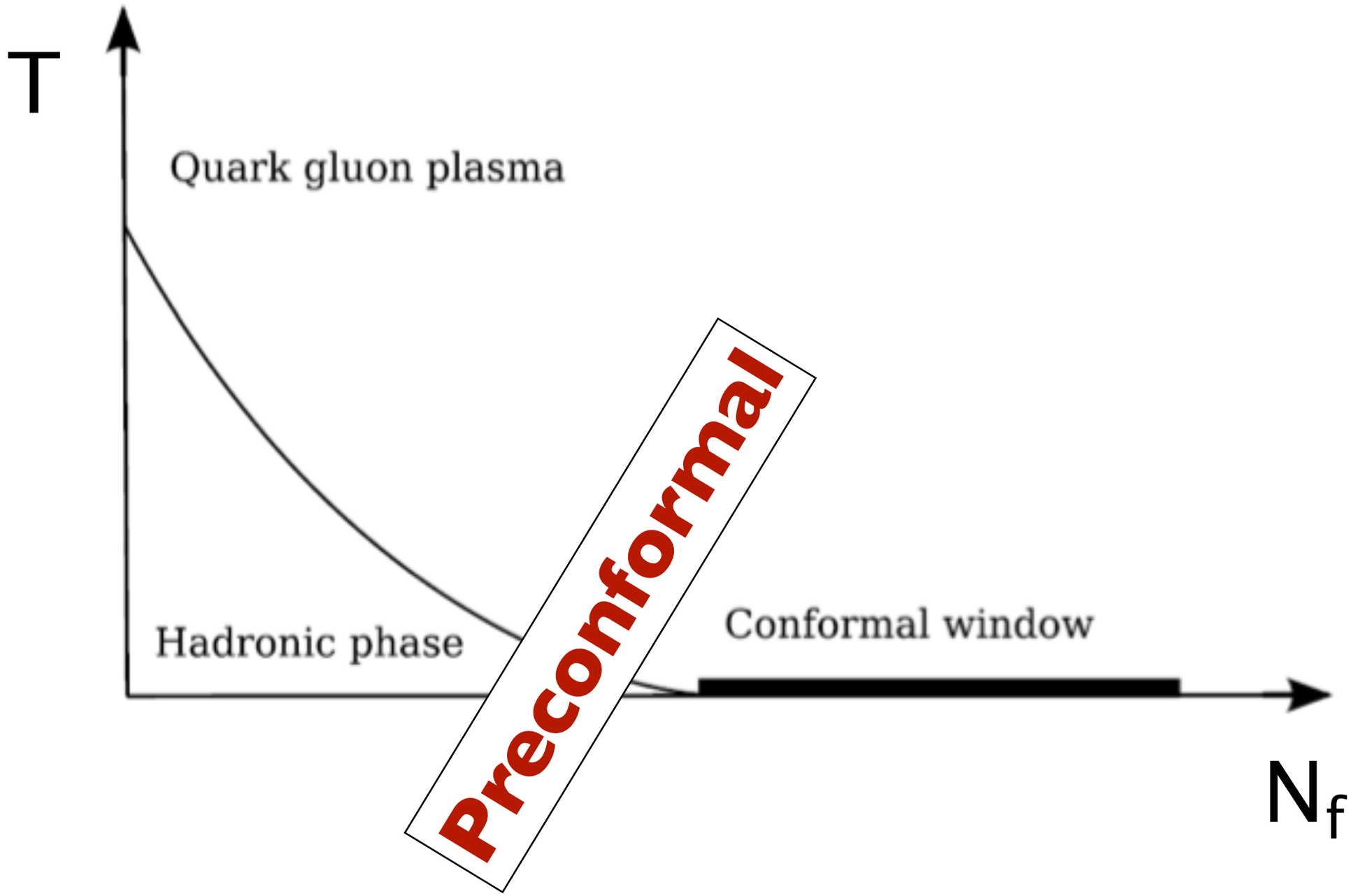
2008 Nf=8 “is” in the QCD phase (massive case)

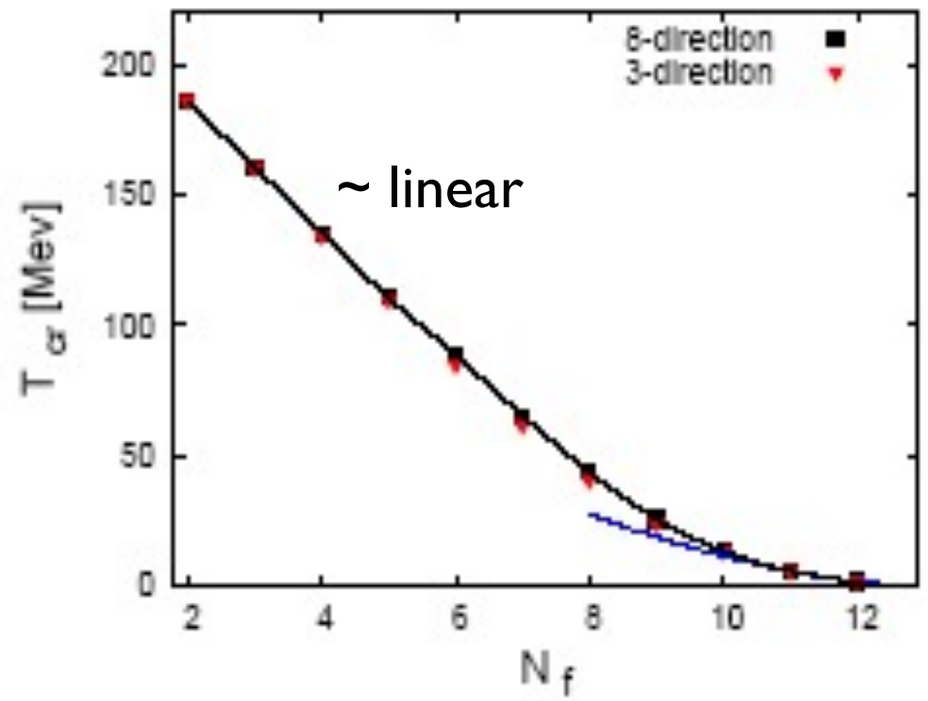
2009 Nf=12 “is” in the conformal window
(there is a conformal window)

Deuzeman, Lombardo EP 2008 2009

Many studies in recent years for different fermion representations and for varying Nf and Nc

Just below the conformal window


T
Quark gluon plasma
Hadronic phase
Conformal window
N_f
Preconformal



Braun, Gies '06
Braun, Fischer, Gies '10

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

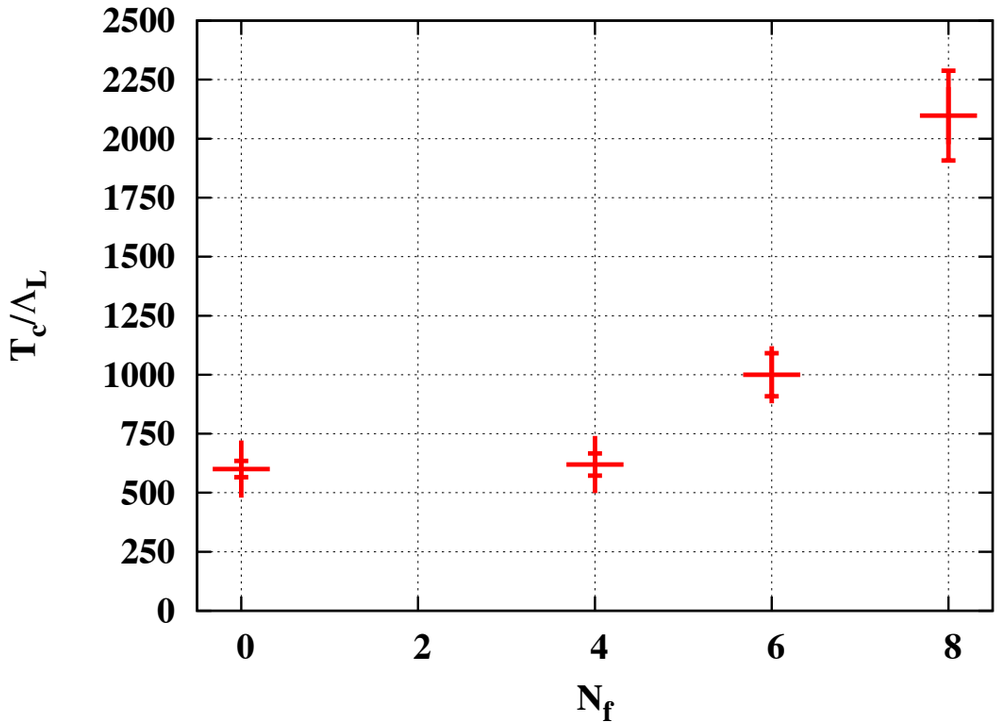
power-law
(due to running coupling)

exponential-law
(Miransky-BKT scaling)

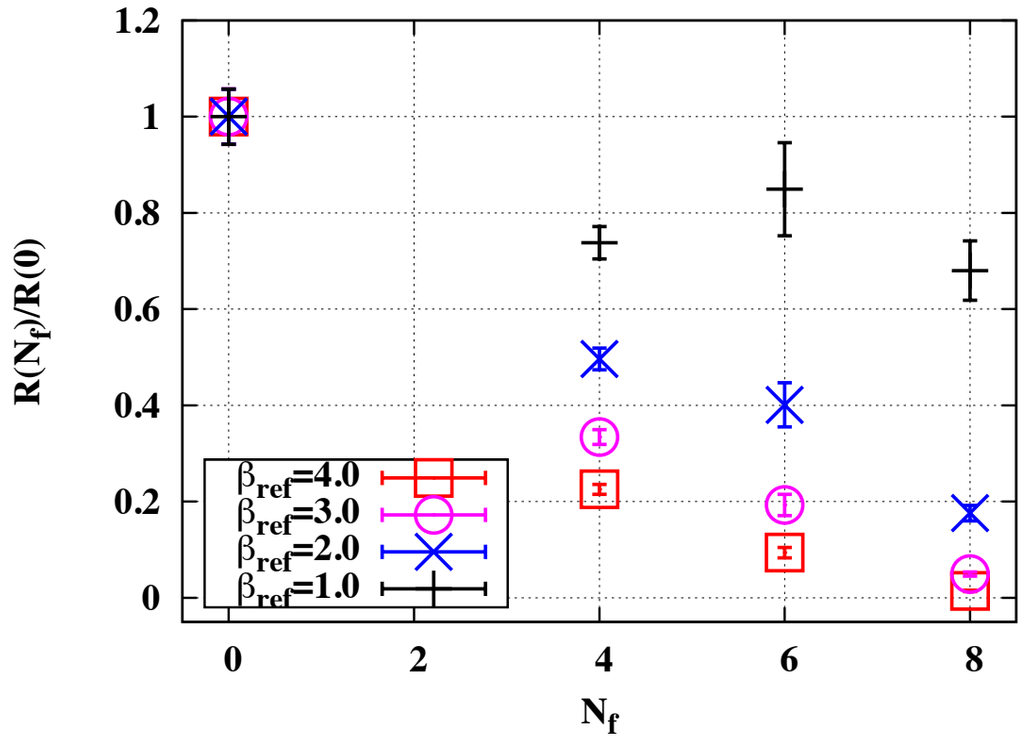
$\bar\psi\psi$, T_c

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

From a IR scale to a UV scale



[Miura, Lombardo, EP '11]



$$\frac{T_c}{\Lambda_L} \cdot a(\beta_c)\Lambda_L = \frac{1}{N_t} \qquad \begin{array}{l}\text{UV} \rightarrow \\ \text{IR} \rightarrow\end{array} \quad \frac{\Lambda_{\text{ref}}}{\Lambda_{\text{L}}} = \exp\left[\frac{\beta_{\text{L}}^{\text{ref}}}{4N_c b_0}\right]$$

Very rough extrapolation

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

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

Physics questions

Universal scaling law for the critical Temperature precursor of a conformal phase transition (BKT phase transition) ⇒ preconformal IR dynamics

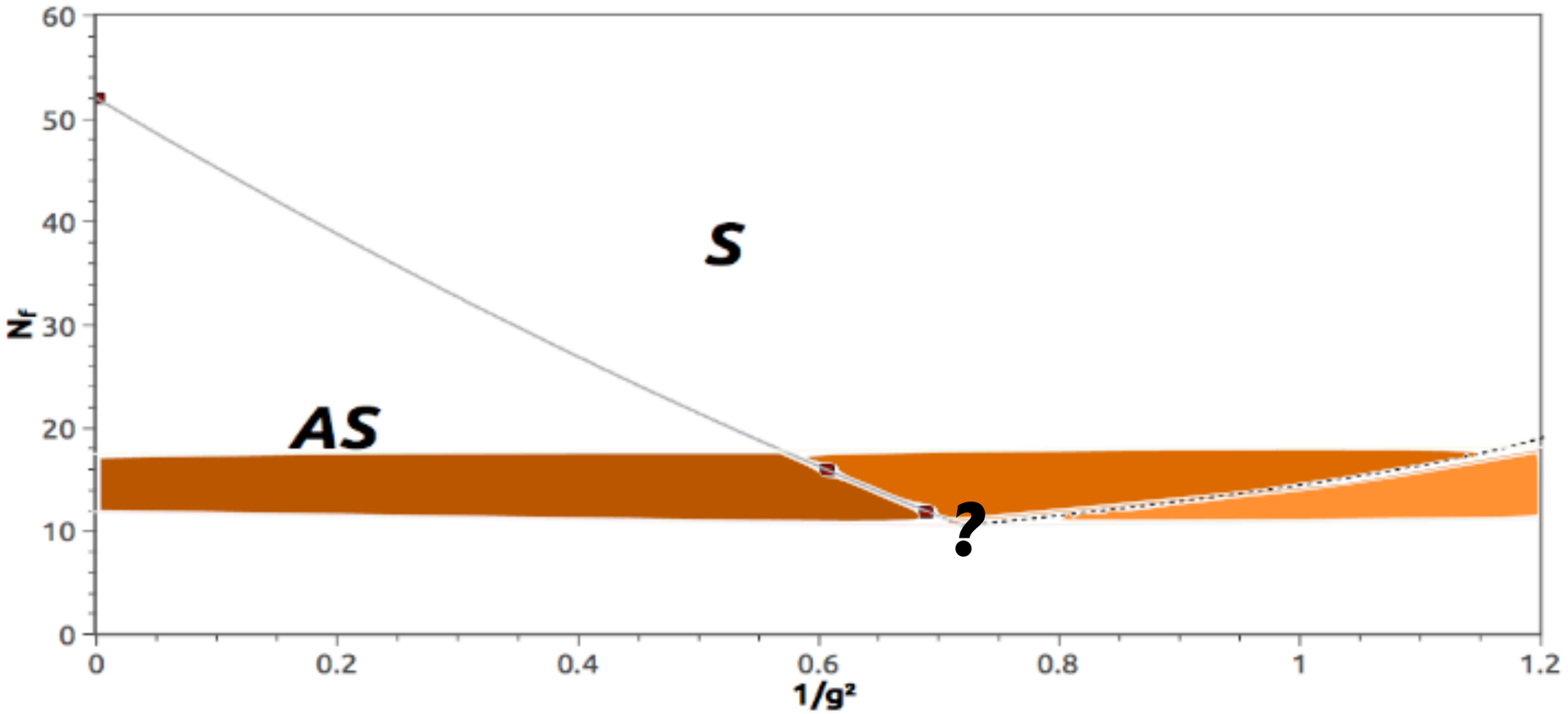
How large is the anomalous dimension γ at the would-be IR fixed point?

What is the ratio of the Higgs and rho masses?

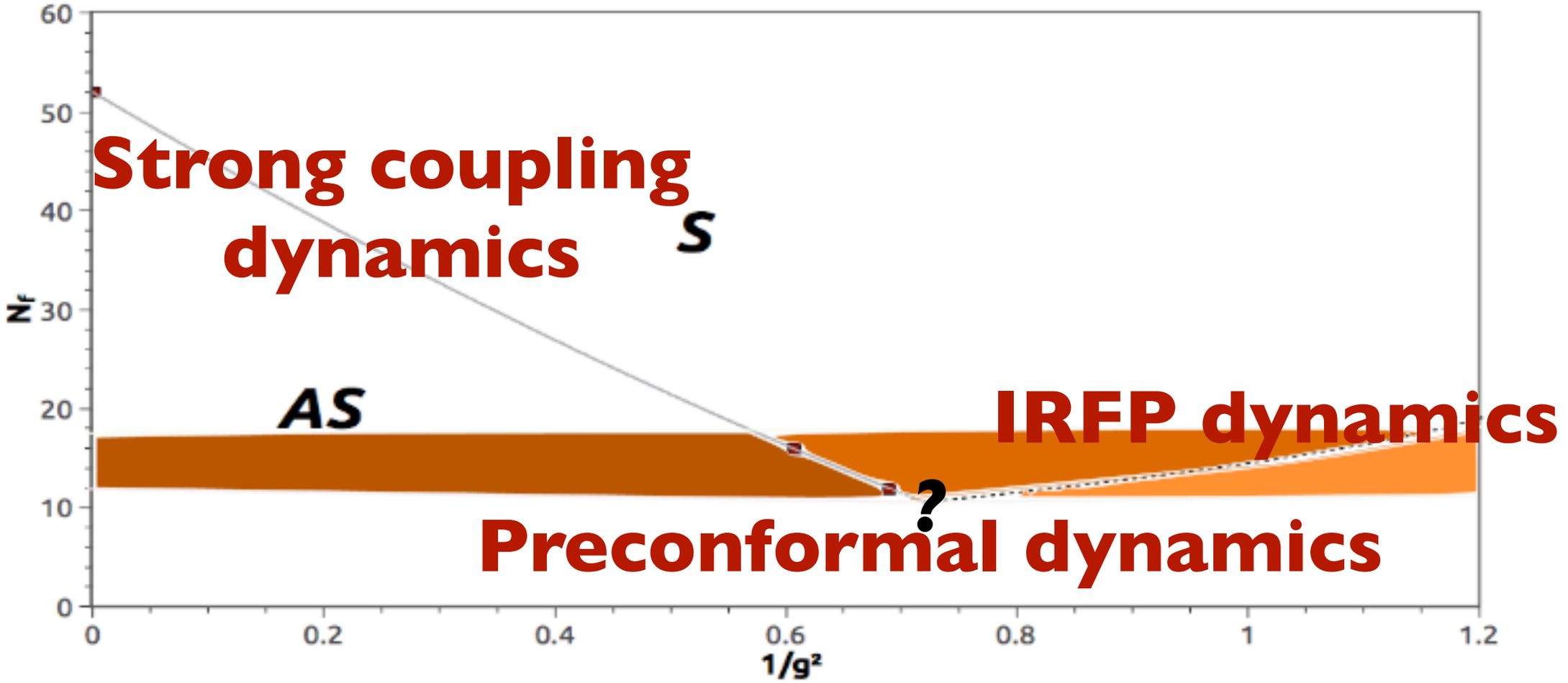
Or, is a different mechanism in place?

Inside the Conformal Window

[Deuzeman,Lombardo,Nunes EP '12]



[Deuzeman,Lombardo,Nunes EP '12]



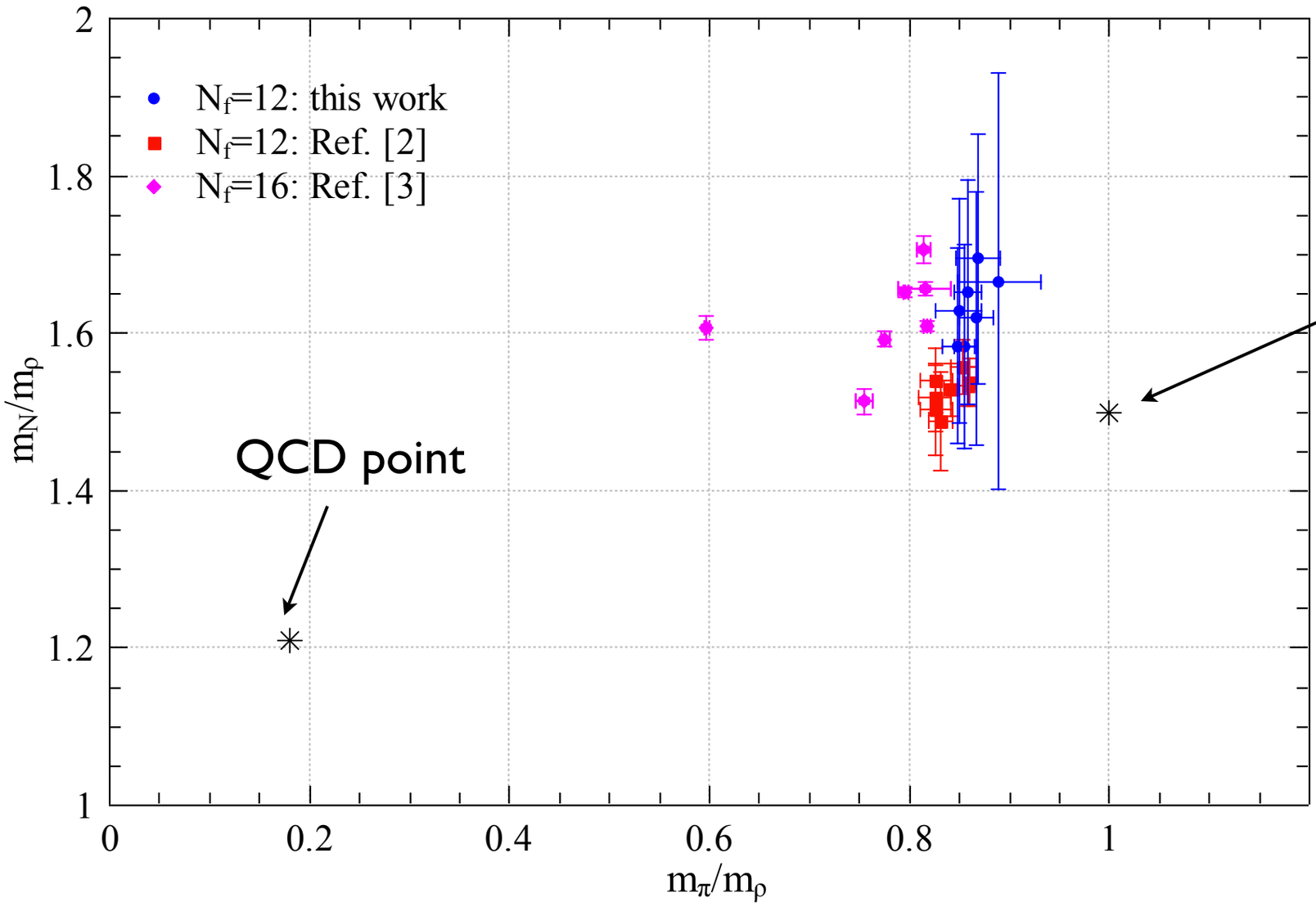
The Spectrum

QCD and non-QCD

$\frac{m_\pi}{m_\rho} \sim \sqrt{m}$	$\frac{m_\pi}{m_\rho} \sim$ const
For fixed lattice spacing:	
$(\frac{am_\pi}{am})^2 \sim$ const	$\frac{(am_\pi)^2}{am} \sim \frac{(am)^{2\delta \to 2}}{am} \sim (am)^{2\delta-1}$ $\quad 0.5<\delta\lesssim 1$

Corrections to power laws are present for an interacting theory not at FP
(and finite volume)

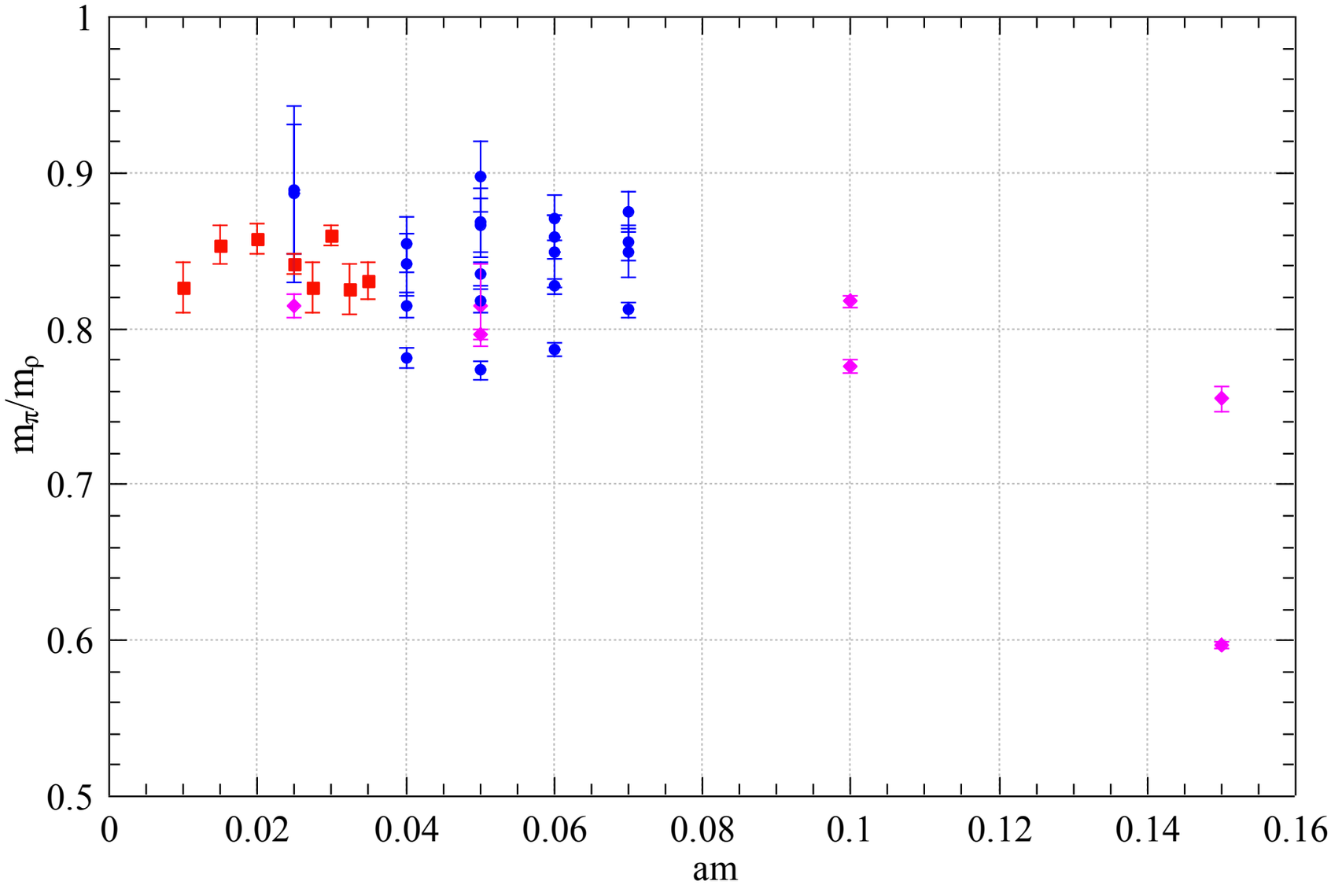
The Edinburgh Plot of Nf=12 and Nf=16



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

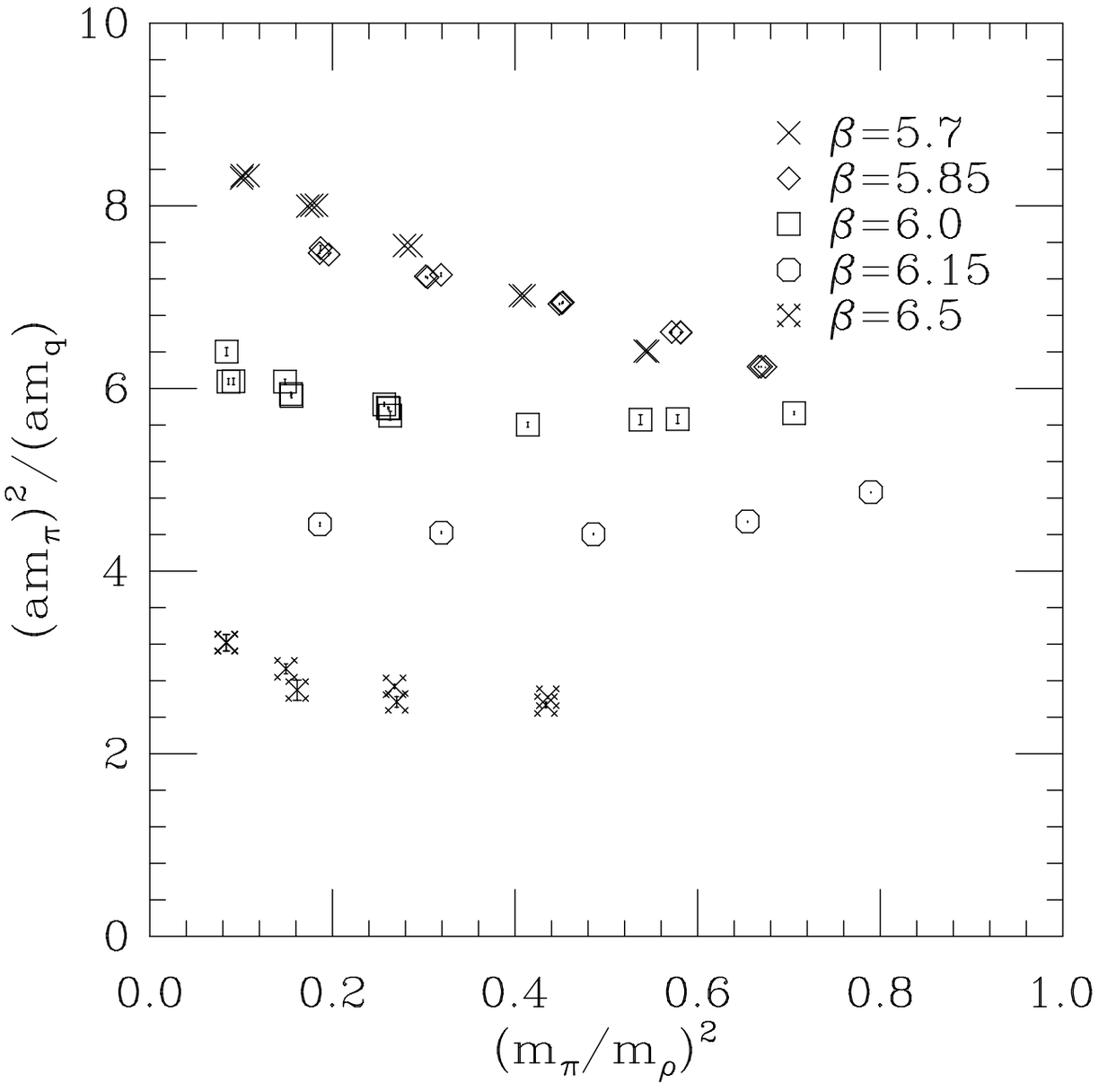
Damgaard, Heller, Krasnitz, Olesen 1997
Fodor, Holland, Kuti, Nogradi, Schroeder 2011

Masses and Power Laws



The ratio is approximately constant in a chirally symmetric phase.
It goes to zero in the chiral (massless) limit of QCD.

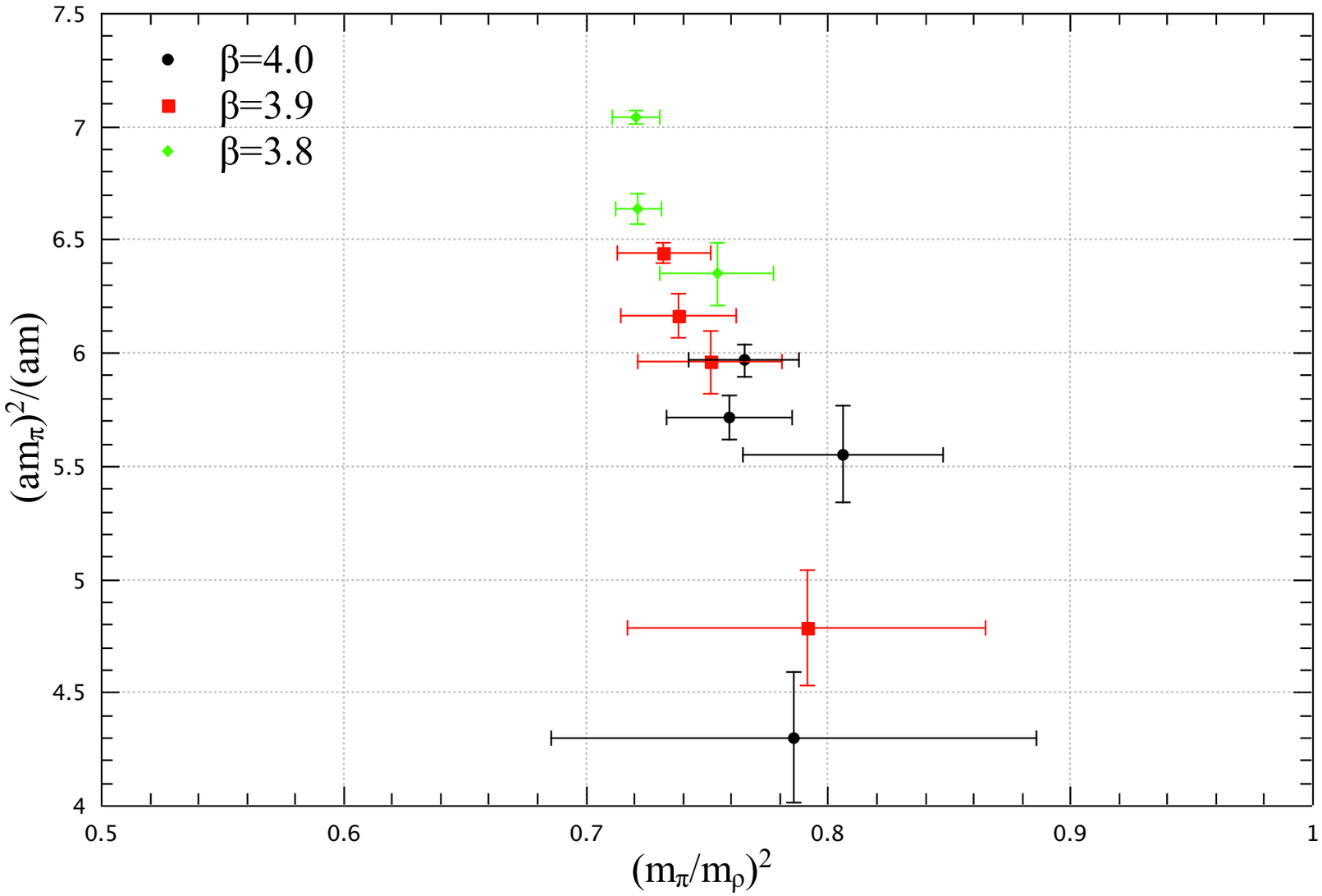
QCD



↑ Ratio increases

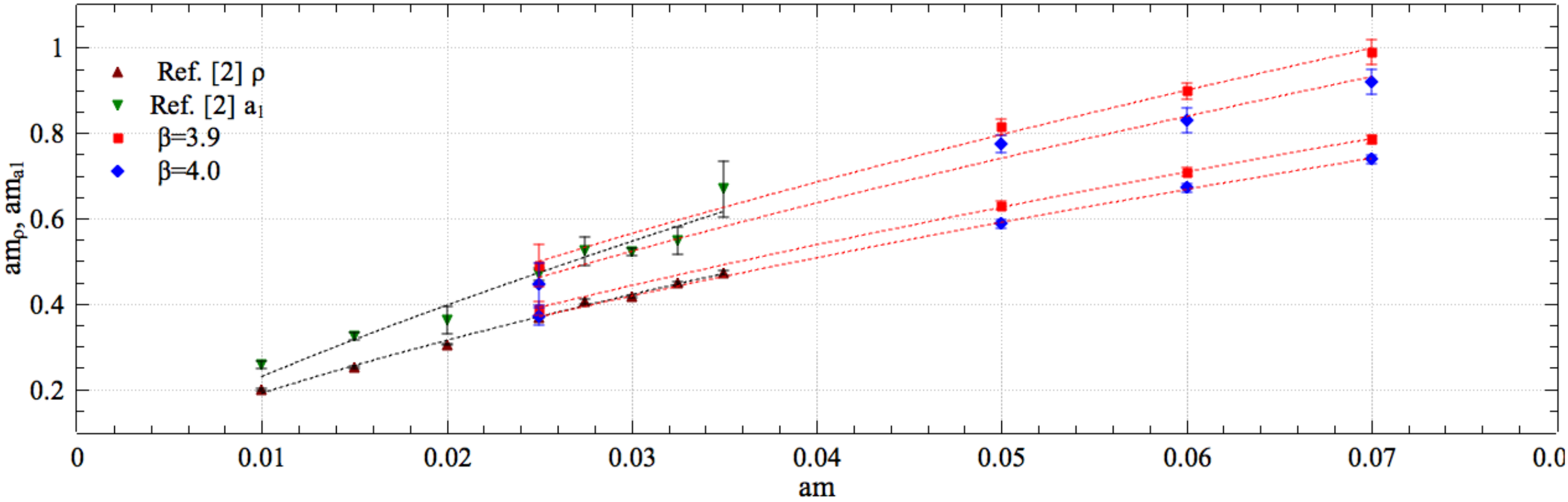
This is compatible with a negative β function

and non-QCD



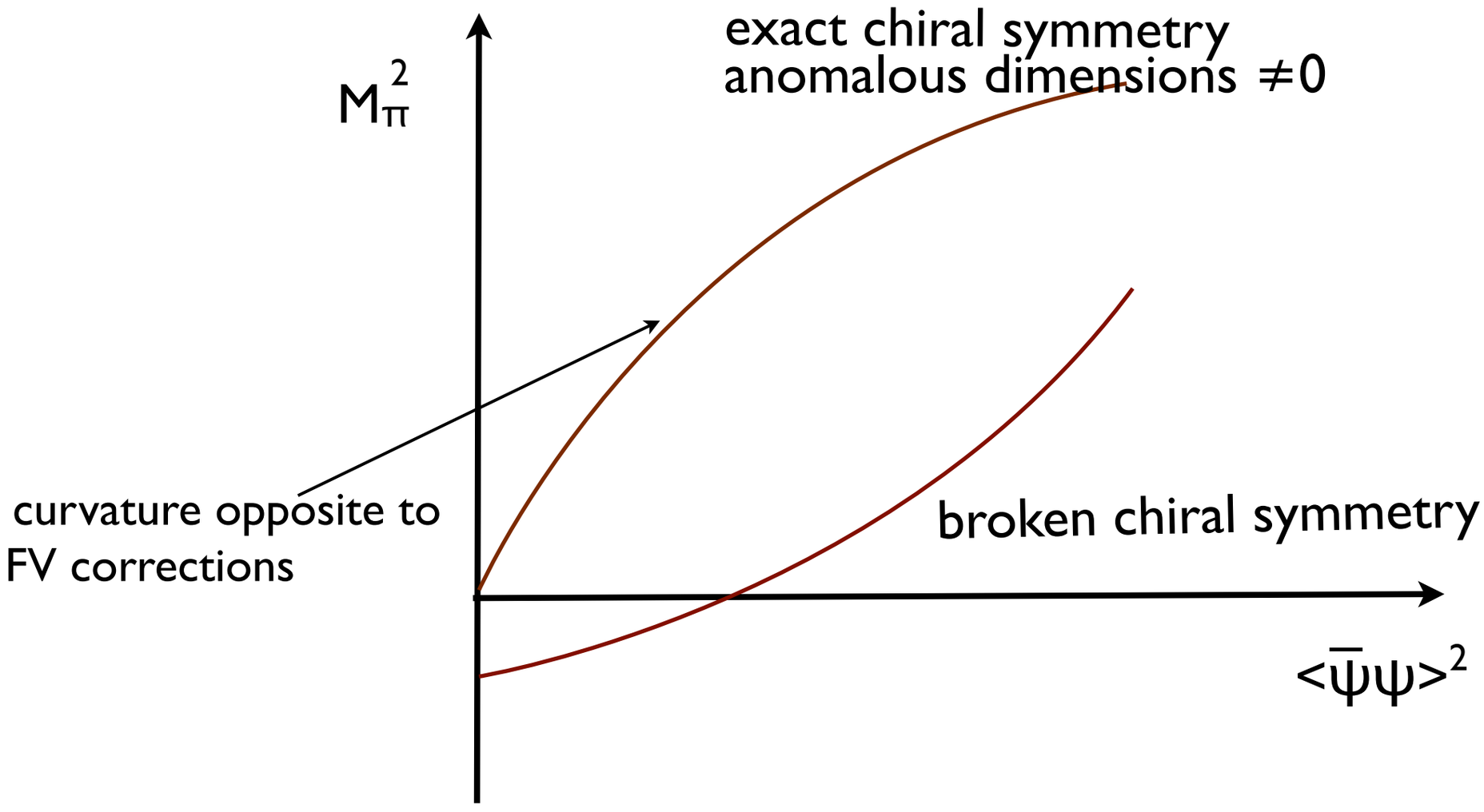
For a fixed m_π/m_ρ the inverted behavior with β_L is compatible with a positive β function

The axial-vector mass splitting



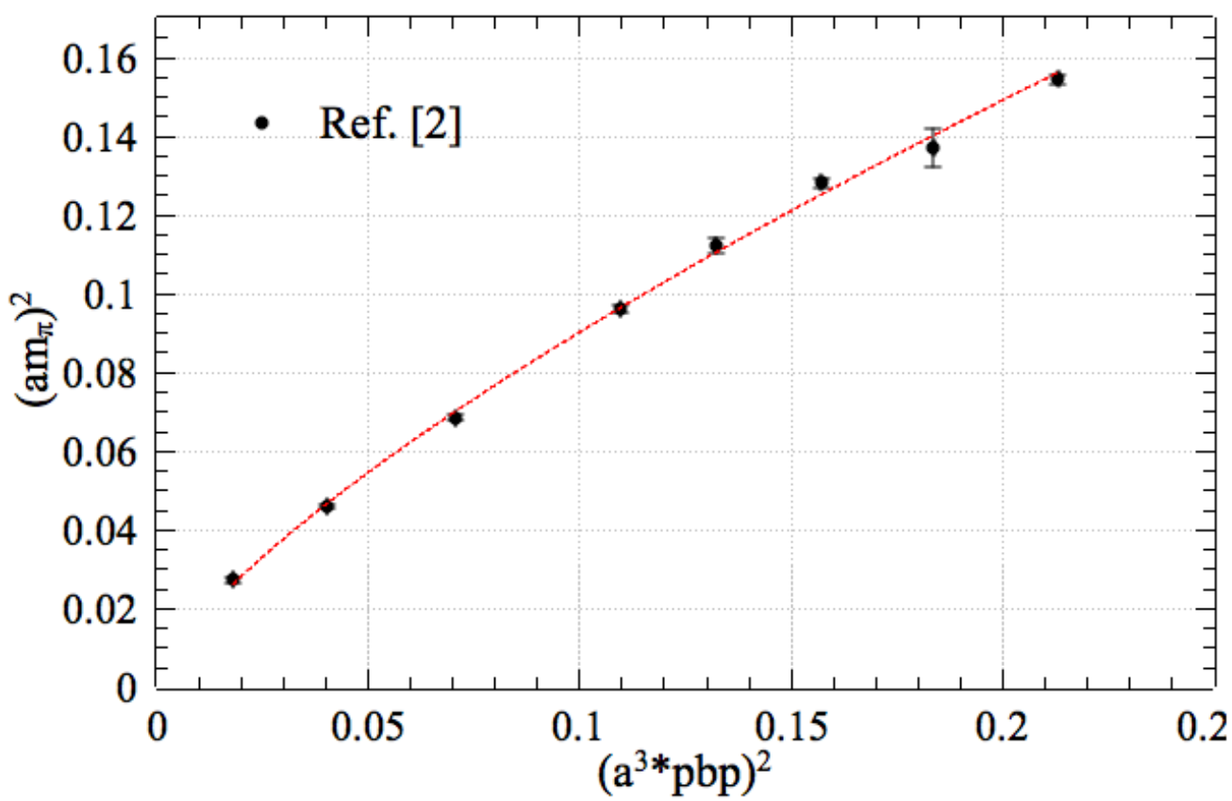
Degeneracy in the chiral (massless) limit signals that chiral symmetry is restored.

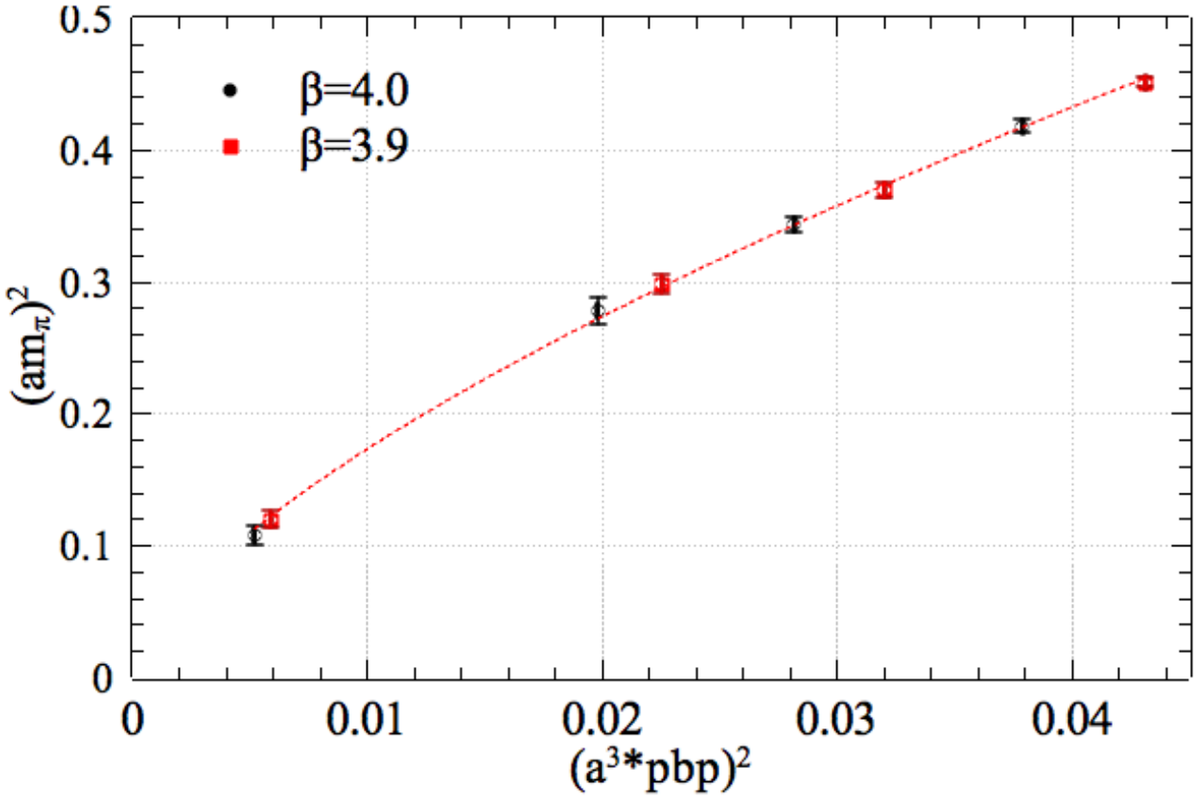
Pseudo Goldstone mass and chiral condensate



Kocic Kogut Lombardo 1993

Nf=12: lattice data

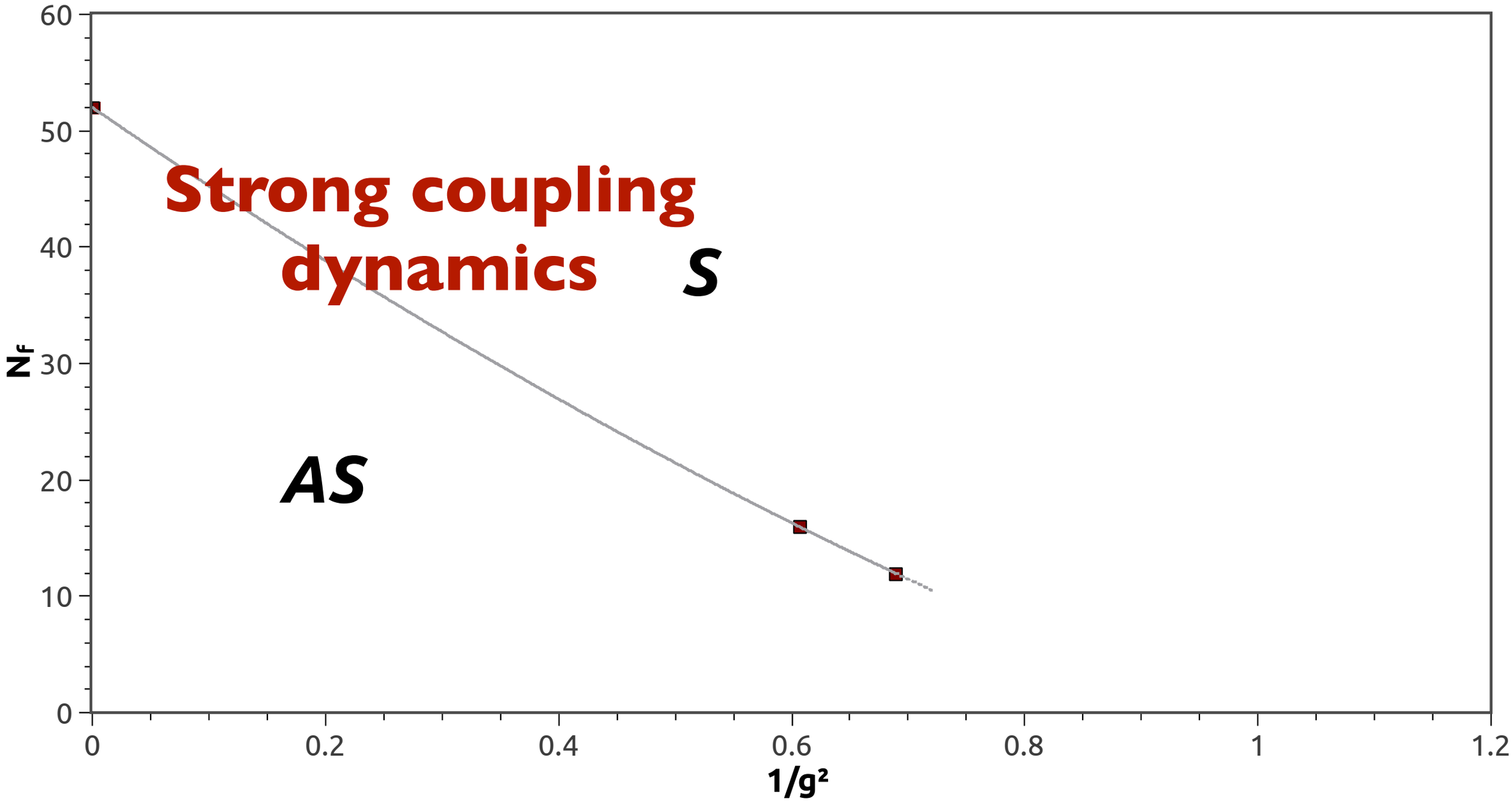




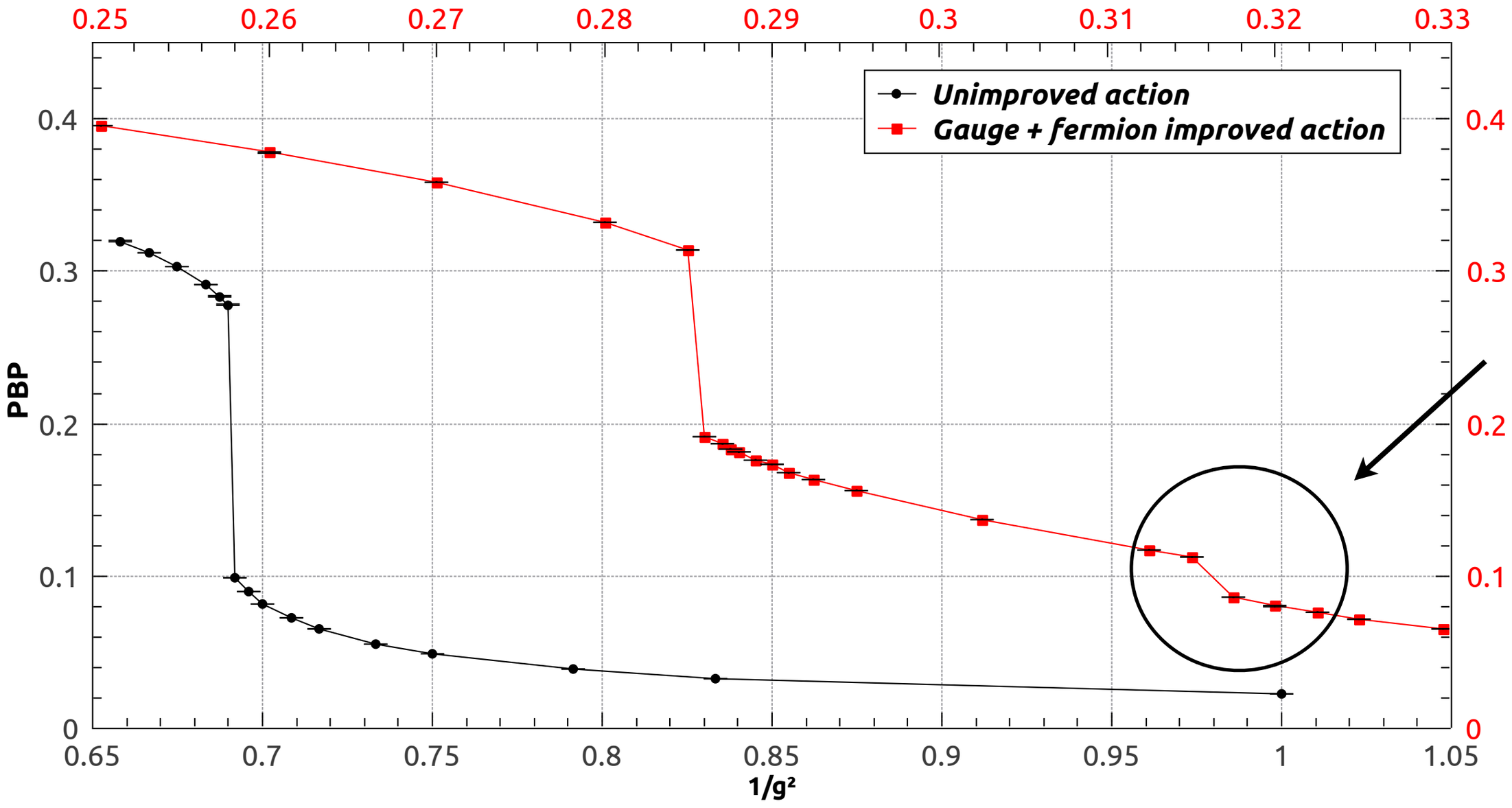
Exact chiral symmetry with non zero anomalous dimensions

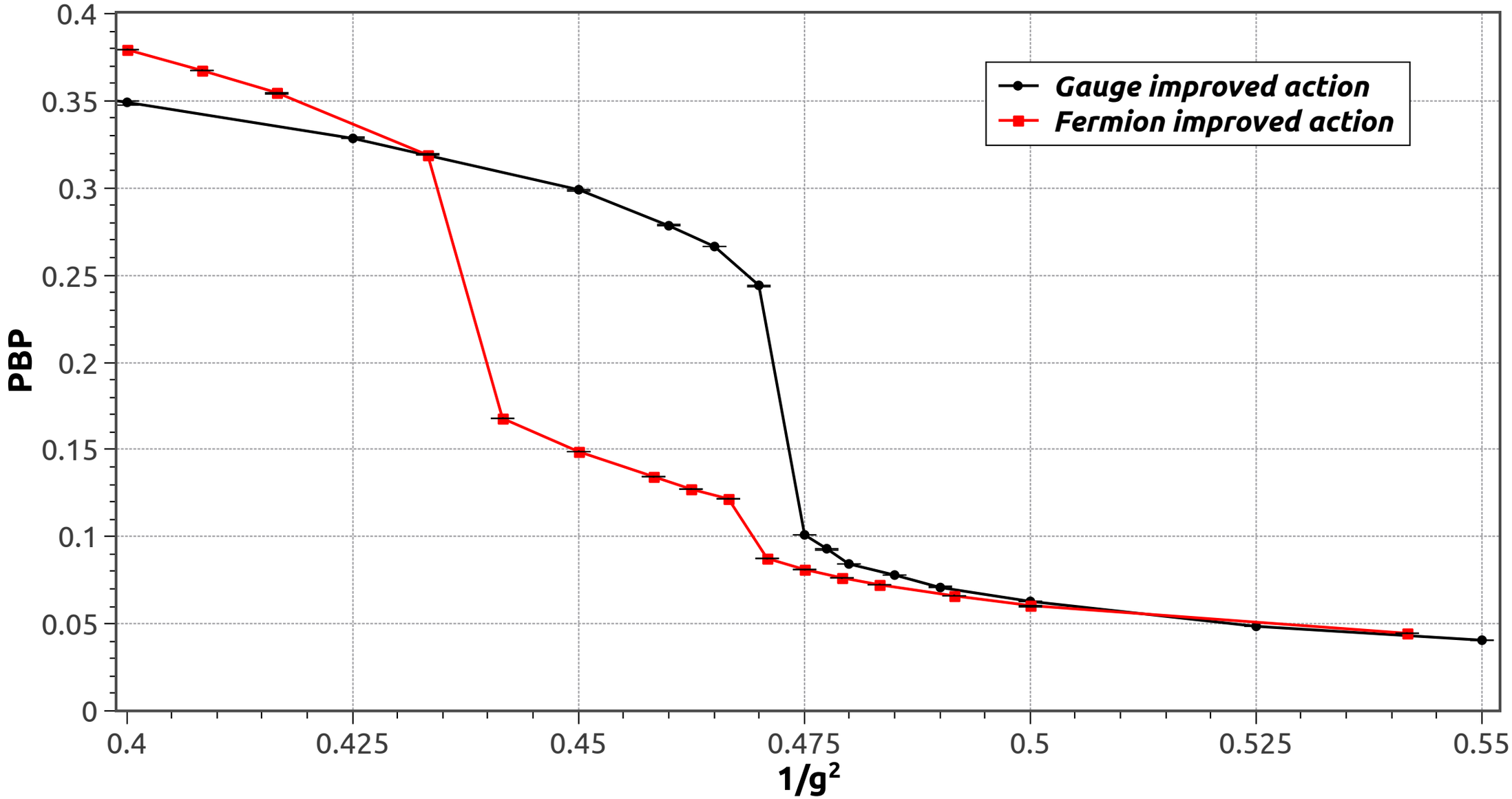
Strong coupling dynamics and bulk transitions

[Deuzeman,Lombardo,Nunes EP '12]



The bulk transition(s)




Gauge improved action
Fermion improved action
PBP
1/g²
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:

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

nearest neighbor next-to-nearest neighbor

Fermion action:

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

} 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

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

$n(\mu = 0)$ **=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

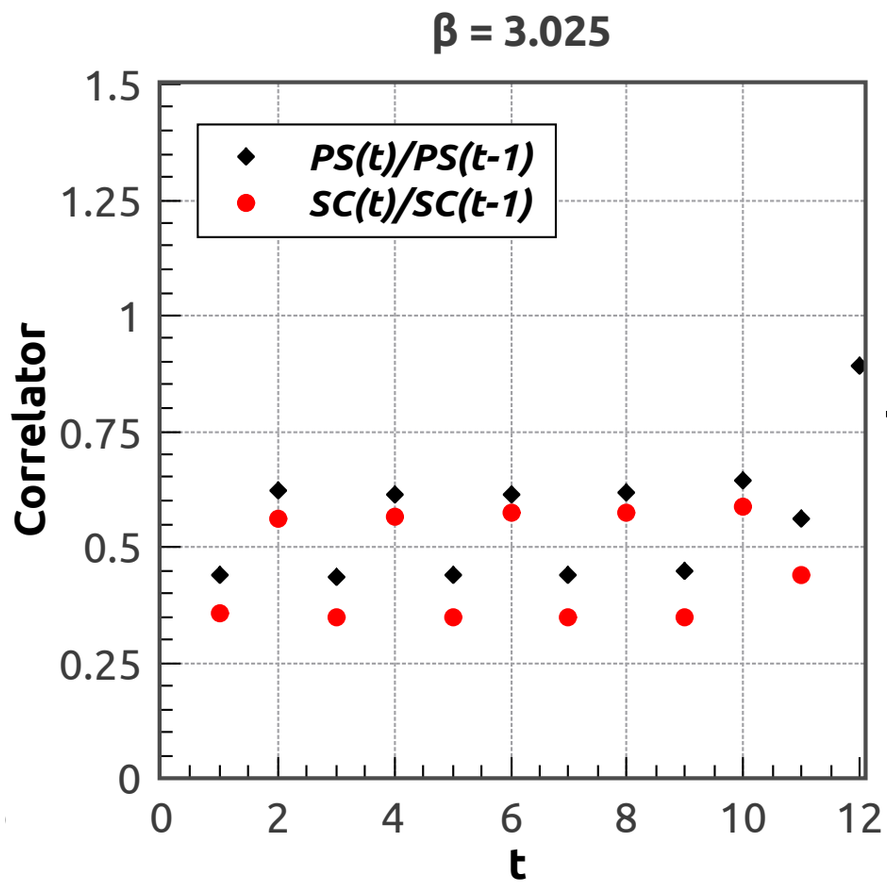
*Plausibly related to S_4 ($T=S_4^2$) investigated by Cheng, Hasenfratz, Schaich '12

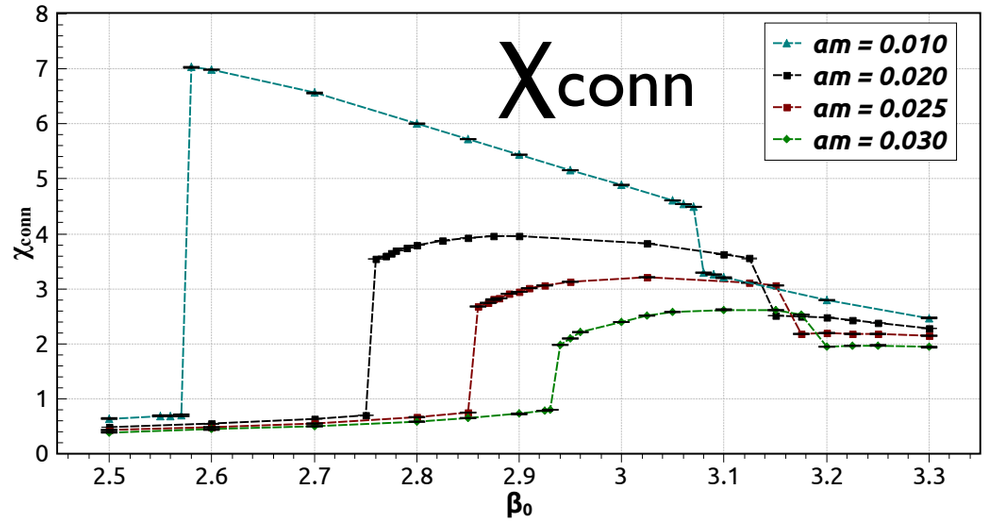
Signatures

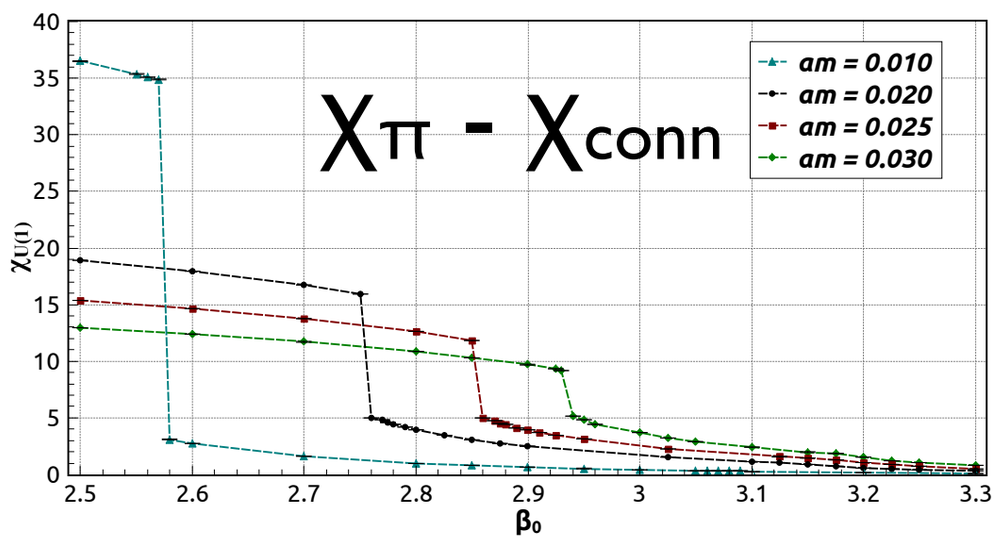
Propagators Susceptibilities

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

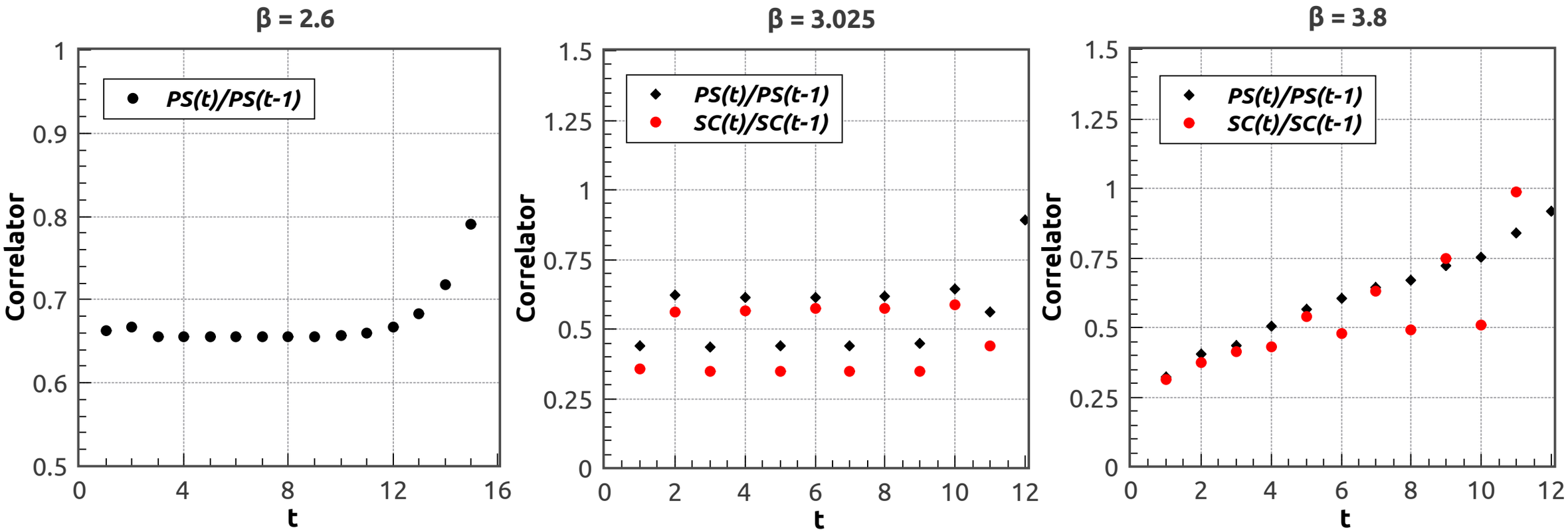
oscillation+asymmetry ⇒ discontinuity





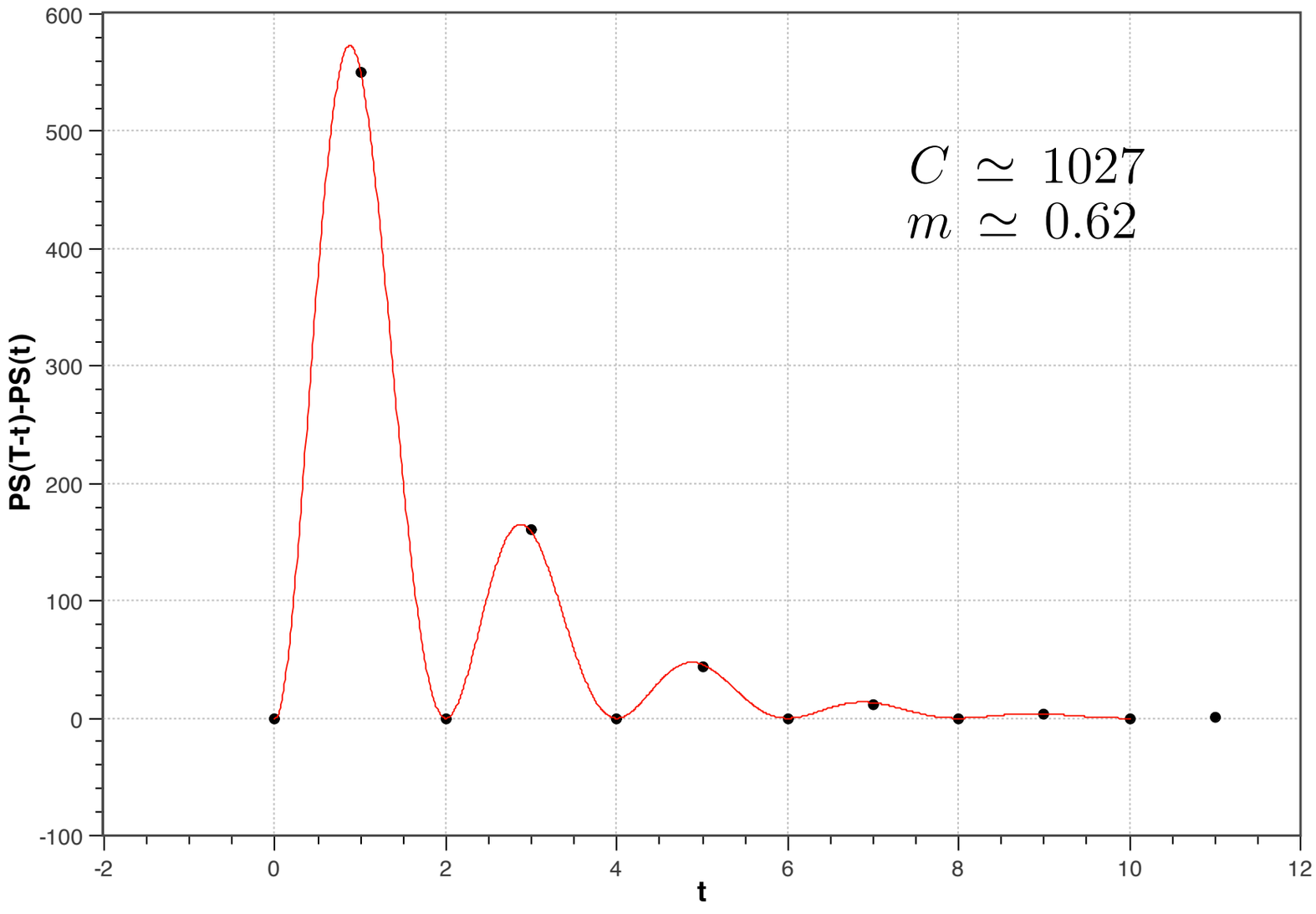


Degeneracy and chiral symmetry



The asymmetry

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



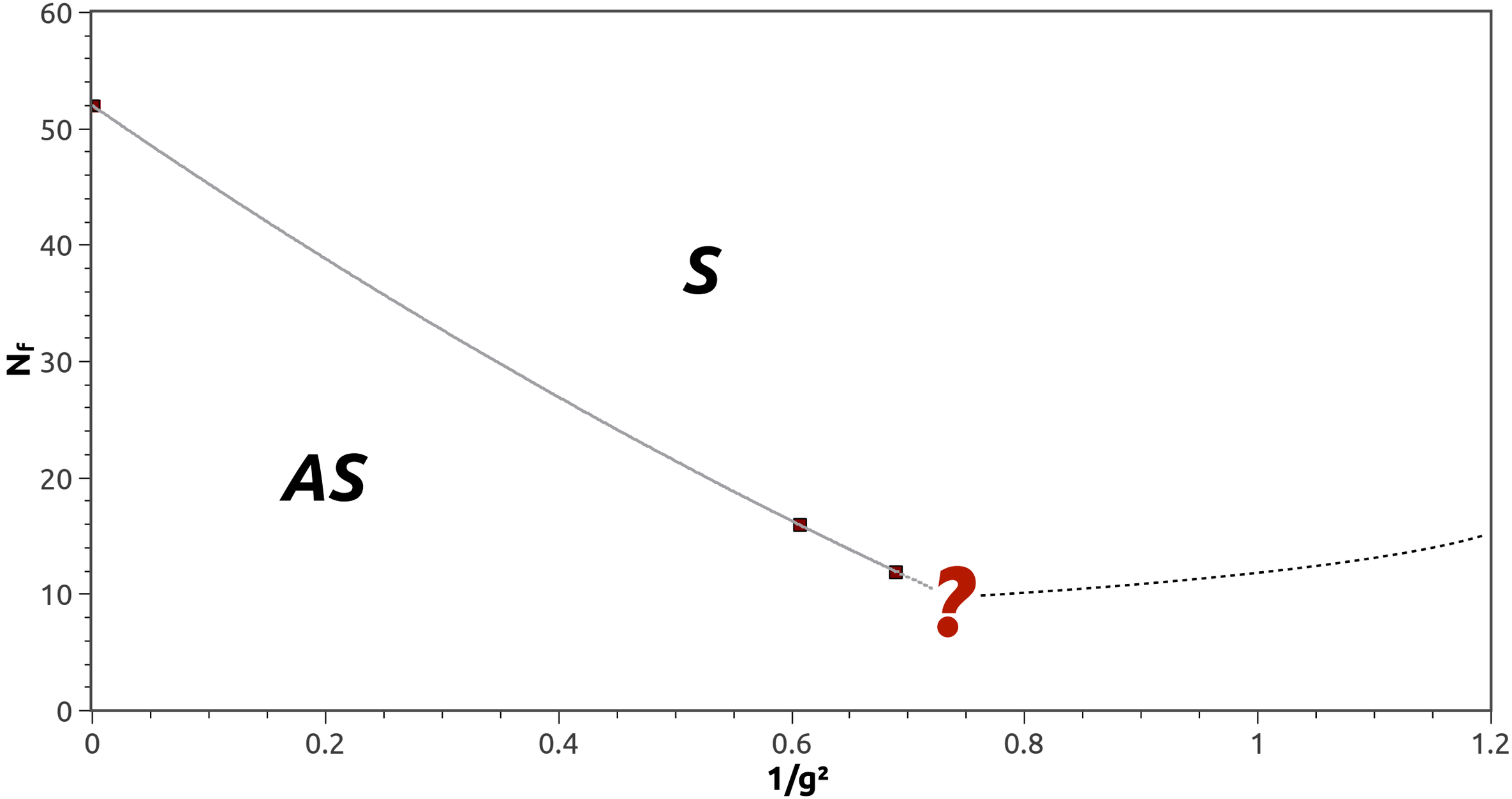
Remarks

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

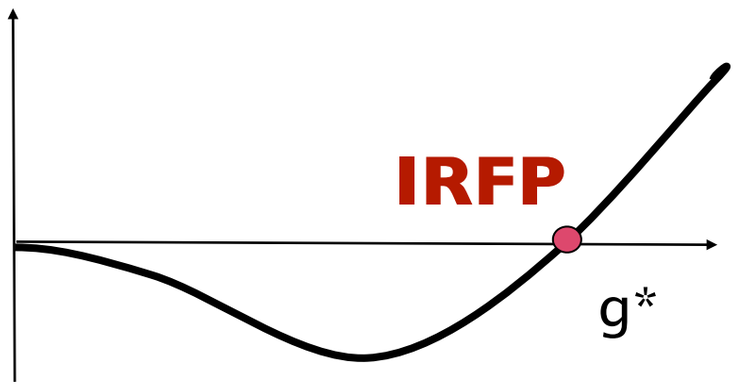
We have found an example where the Naik improvement of the staggered fermion action generates a **new phase of the system** signalled by a discontinuity of the chiral susceptibility (change of mass slope of the chiral condensate)

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

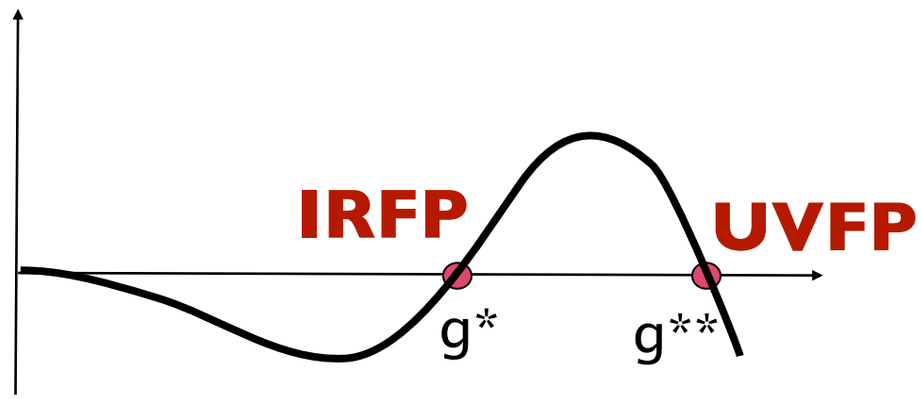
AdS/CFT
and the disappearance of the CW


S
AS
?
N_f
$1/g^2$
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1
1.2

Which scenario is realized ?



SQCD: duality suggests that the (electric) theory is infinitely strongly coupled below the CW
g* flows to infinity



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

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

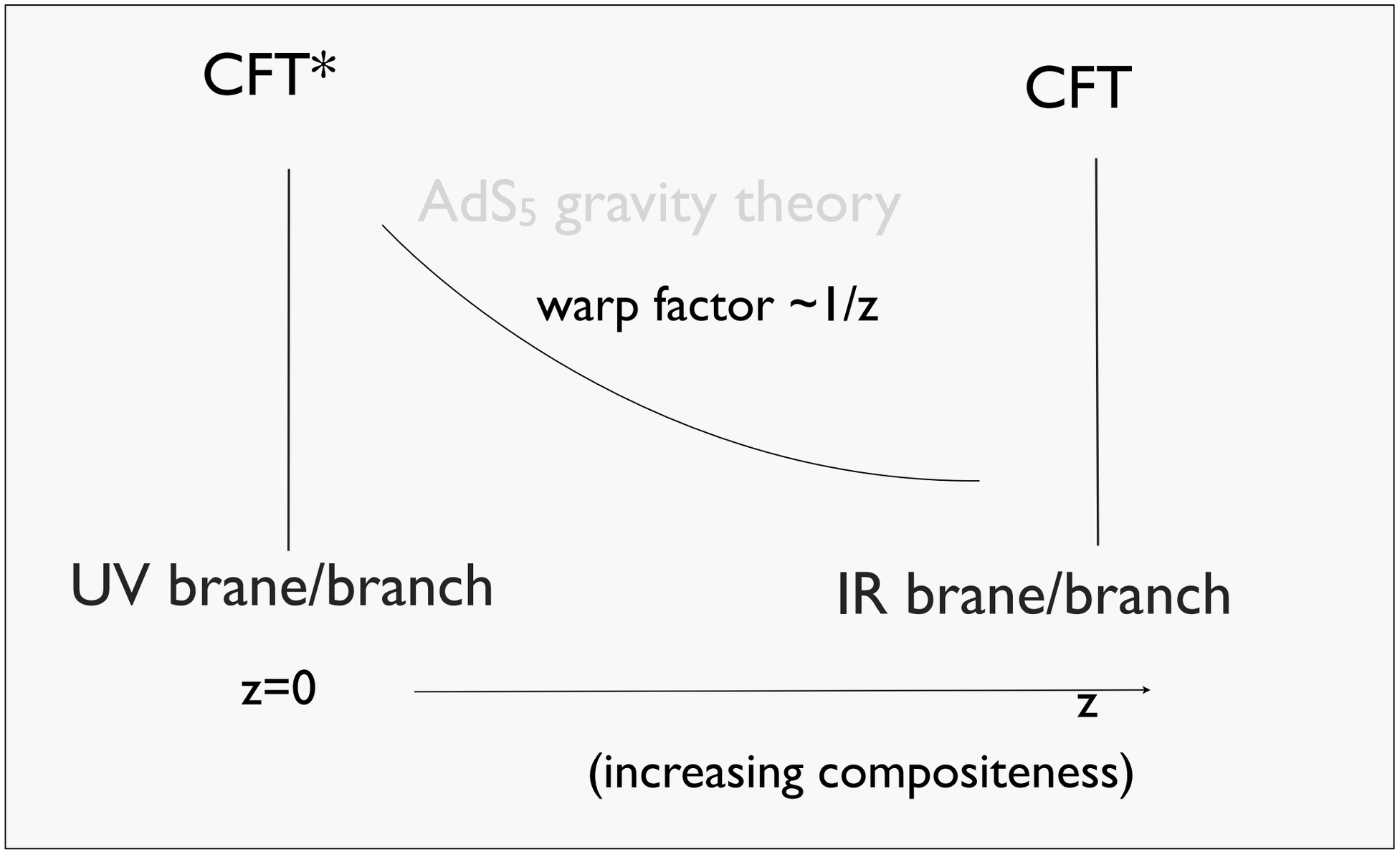
Reproduces 2-loop beta in the (perturbative) Veneziano limit

YM: Bochicchio '08 (EP '09)

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

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: $\beta \to \beta_{\rm NSVZ}(\gamma_0 = -1/2)$
IR limit: ordinary confinement

$N_f = 2N_c$ UVFP at strong coupling

$N_f > 2N_c$ Seiberg dual ($N_c \to N_f$-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.