Conformal Strong Dynamics

theory, signatures and applications

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Based on work done in collaboration with:
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A. Barranco, J. Russo (AdS/CFT)

Outline

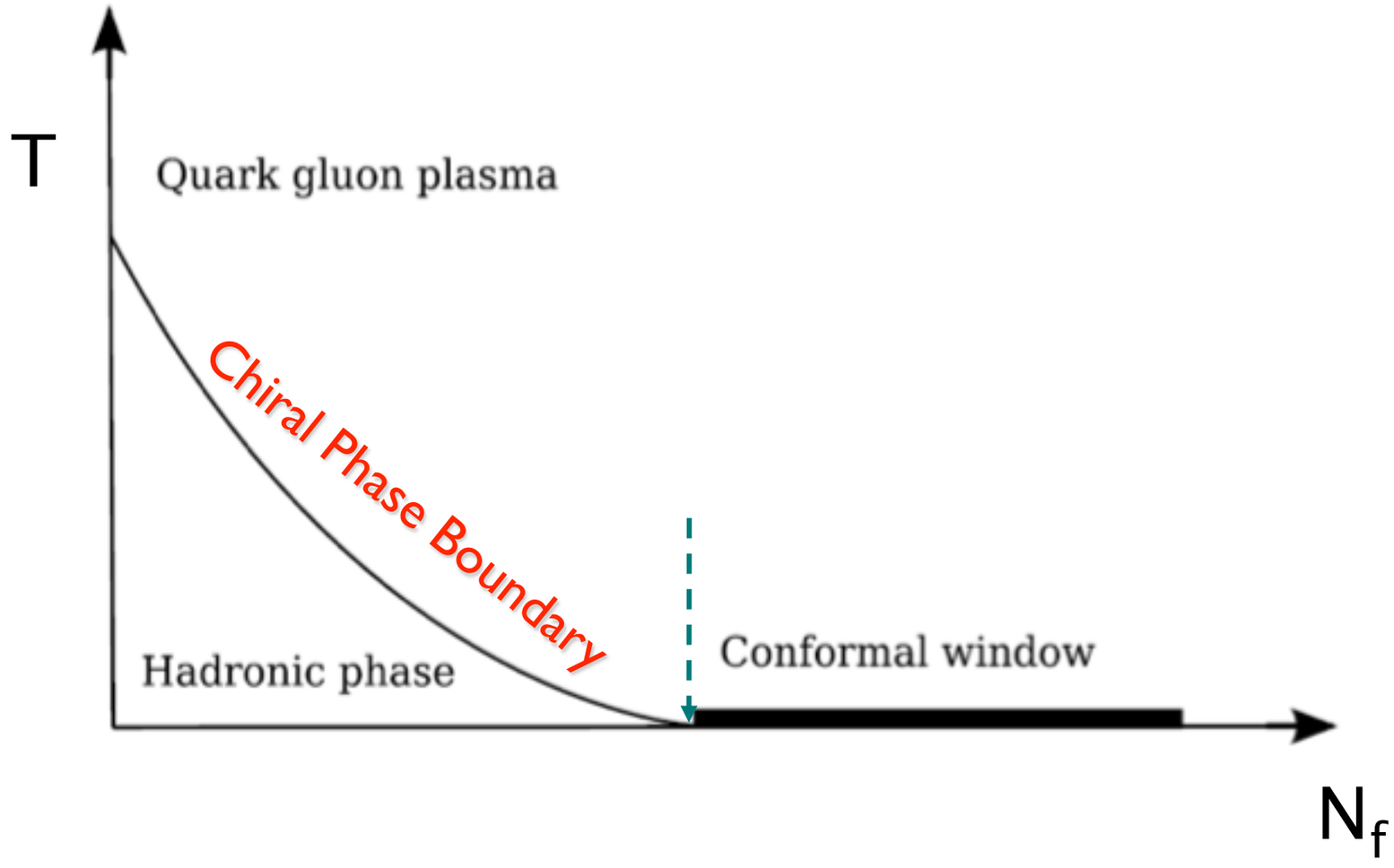
The Phase Diagram: what's new

The conformal side and its signatures
(spectrum & phase transitions)

Preconformal dynamics

Disappearance of conformality with AdS/CFT

The Phase Diagram I: Temperature - Flavor



Physics of:

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

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

✓conformal regime (T=0)

Theories of ElectroWeak Symmetry Breaking

Fundamental scalars

SUSY (weakly coupled)

No fundamental scalars

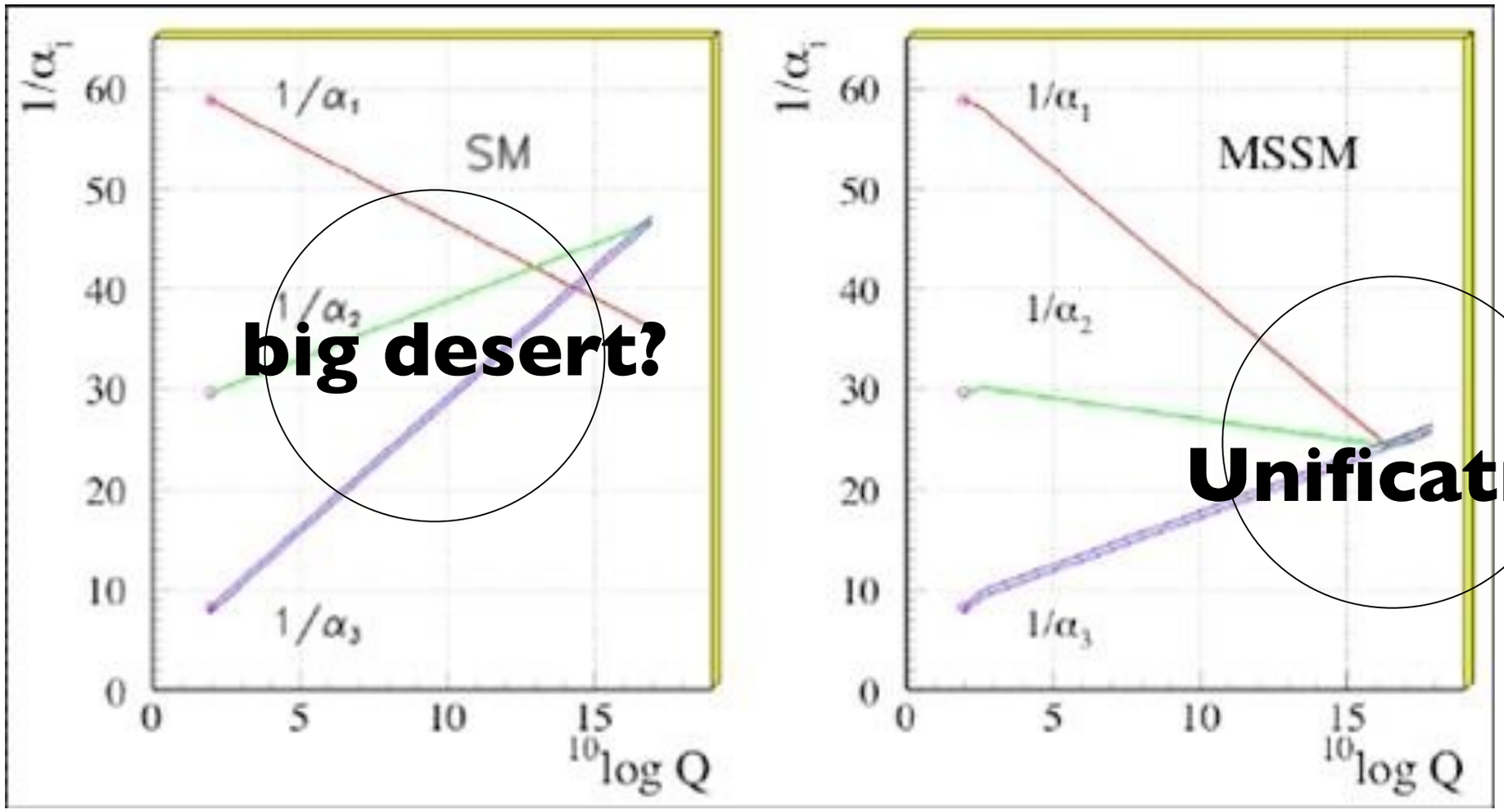
✓Chiral SB in QCD (strongly)
✓Superconductivity (weakly)

Large and slowly running anomalous dimensions

$$\langle\bar{\psi}\psi\rangle_{\Lambda'} = \langle\bar{\psi}\psi\rangle_{\Lambda}\, e^{\int_{\Lambda}^{\Lambda'} \frac{d\mu}{\mu}\,\gamma(\mu)} \simeq \langle\bar{\psi}\psi\rangle_{\Lambda} \left(\frac{\Lambda'}{\Lambda}\right)^{\gamma}$$

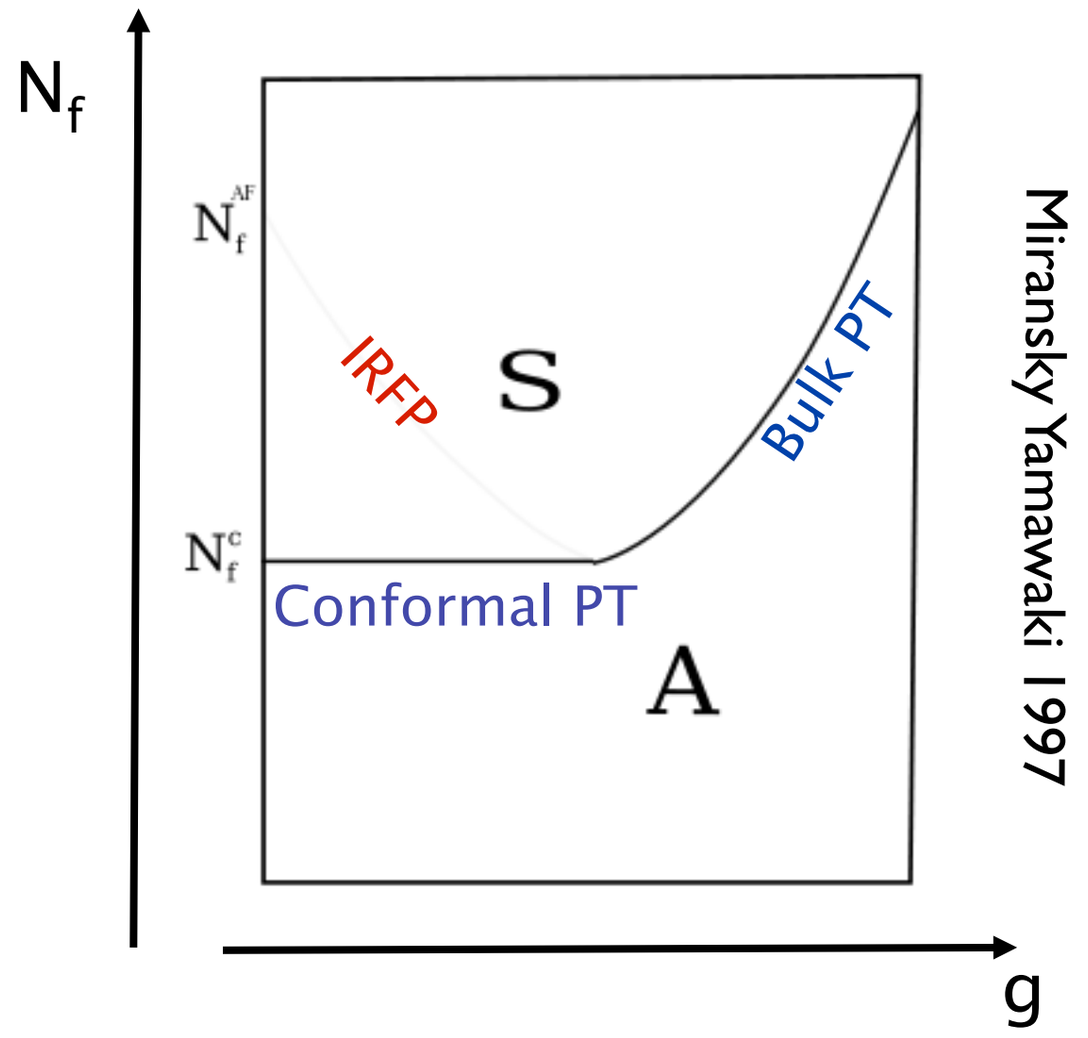
produce a large hierarchy of condensates

Unification of couplings



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

The Phase Diagram II: Flavor - Coupling (T=0)



I	II	III
Exact chiral	Exact chiral	Broken chiral
β<0	β>0	UVFP?

2008 Nf=8 is in the QCD phase

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 Nc

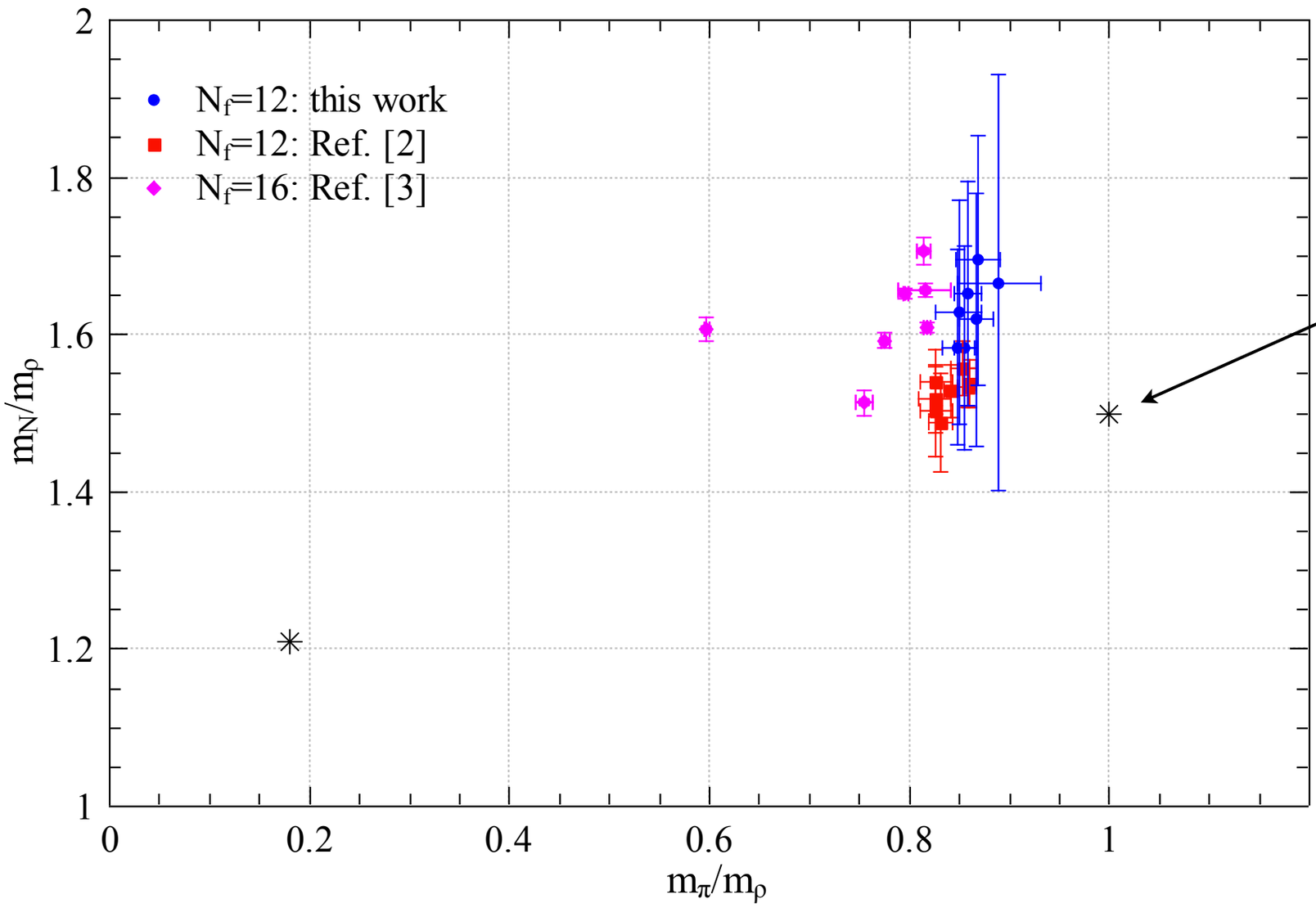
The Spectrum

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



Heavy quark limit or free theory

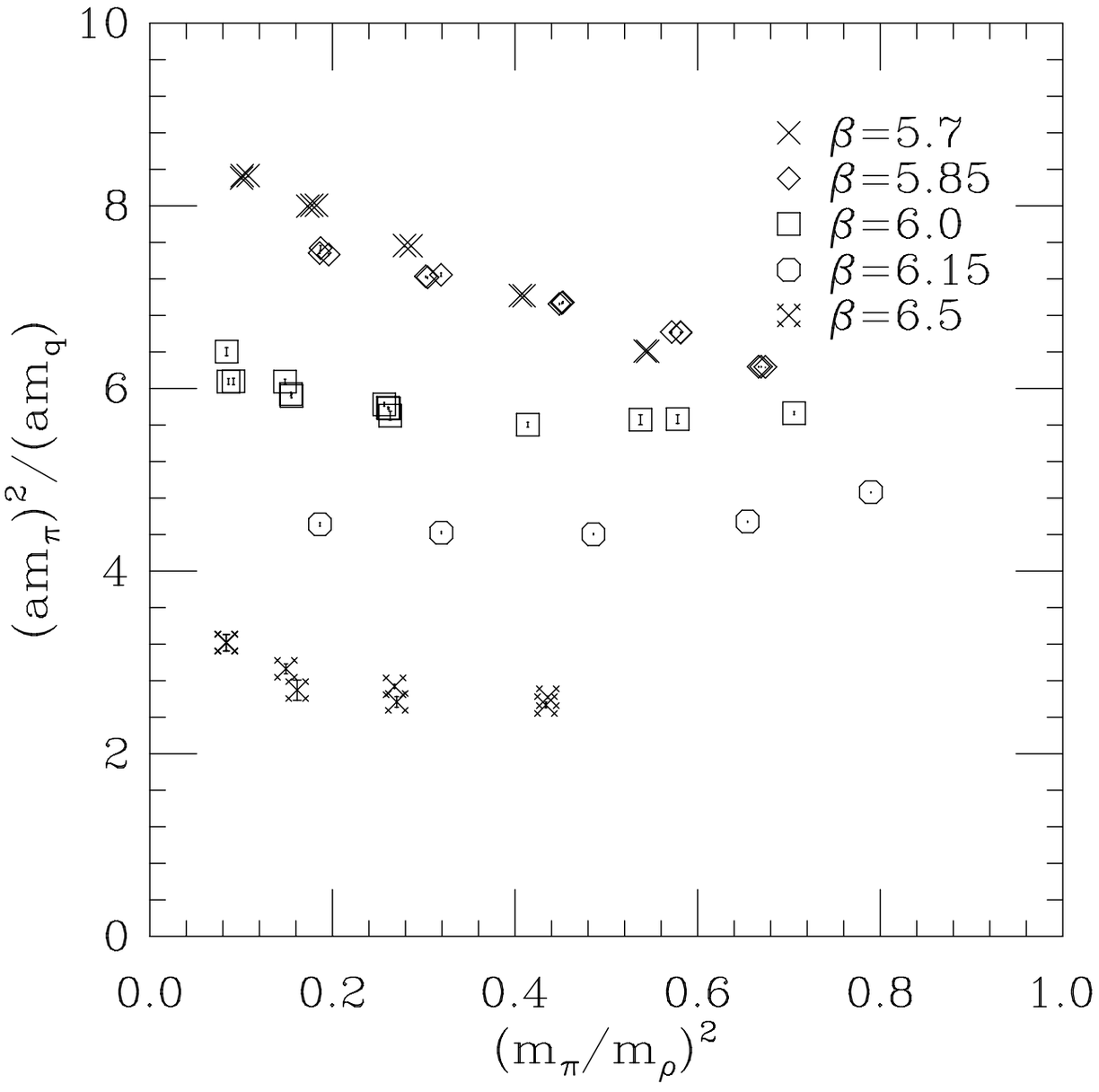
Bare quark masses span a range 0.01 to 0.07 at various β for Nf=12

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

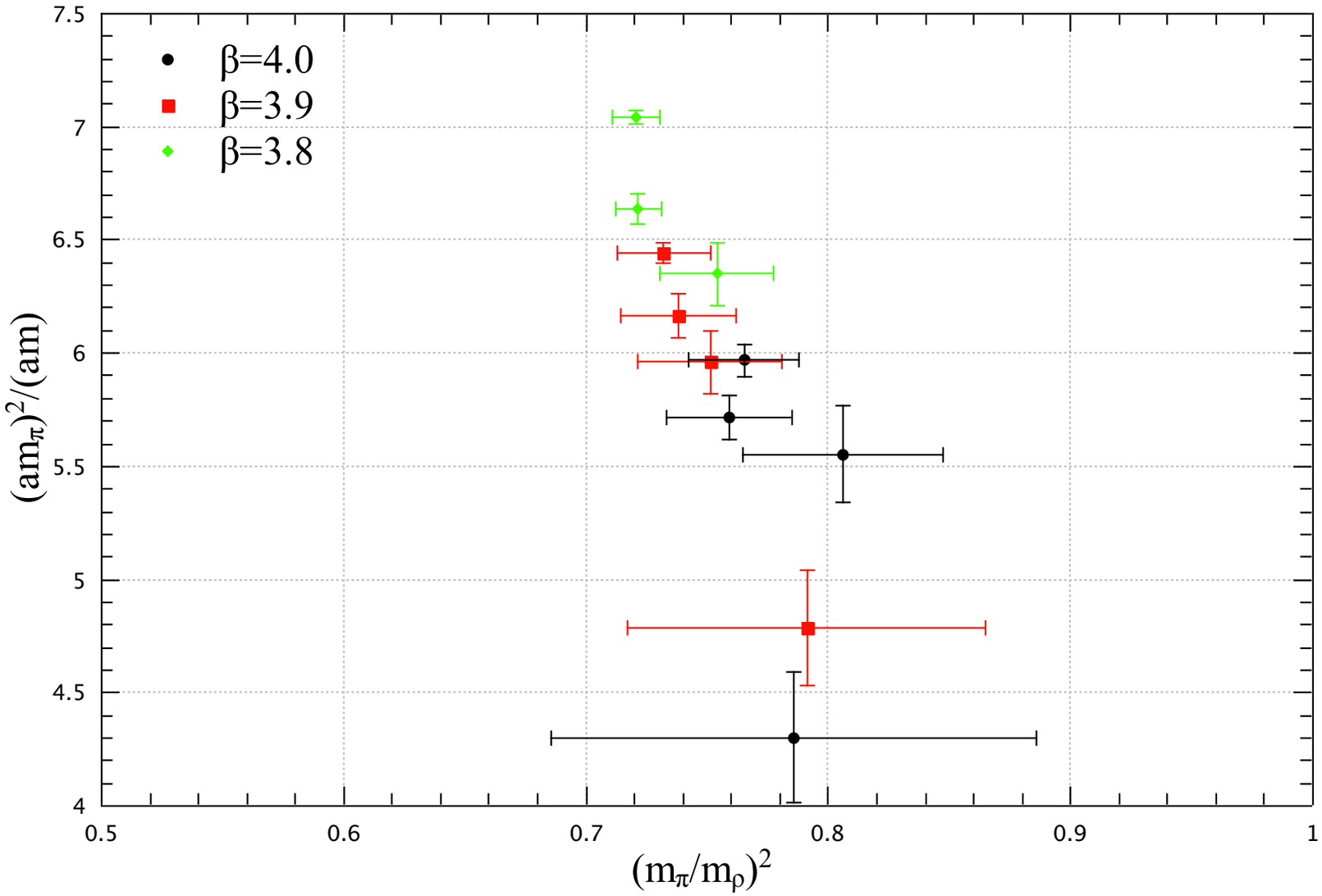
QCD



↑ Ratio increases

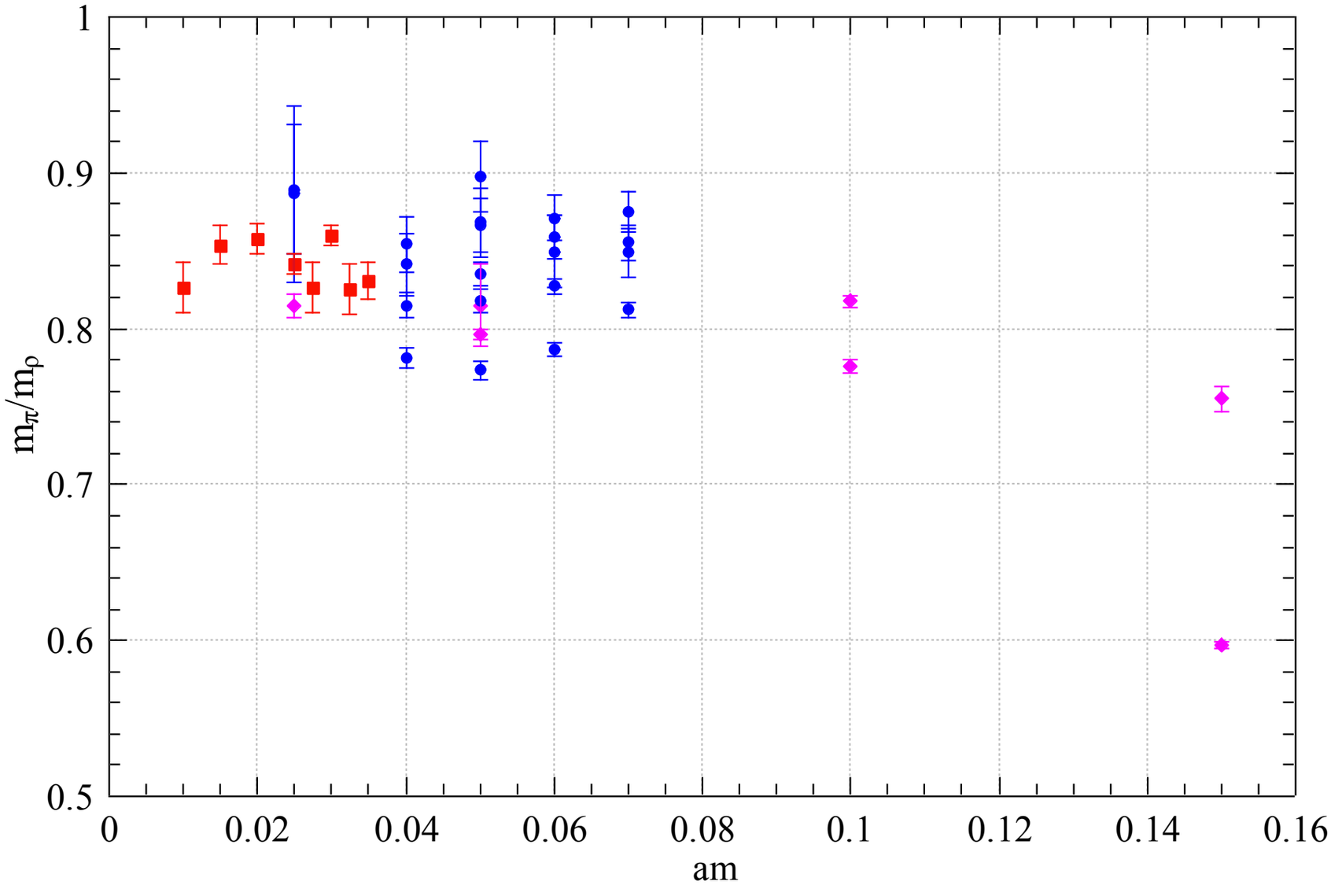
This is compatible with a negative β function

and non-QCD



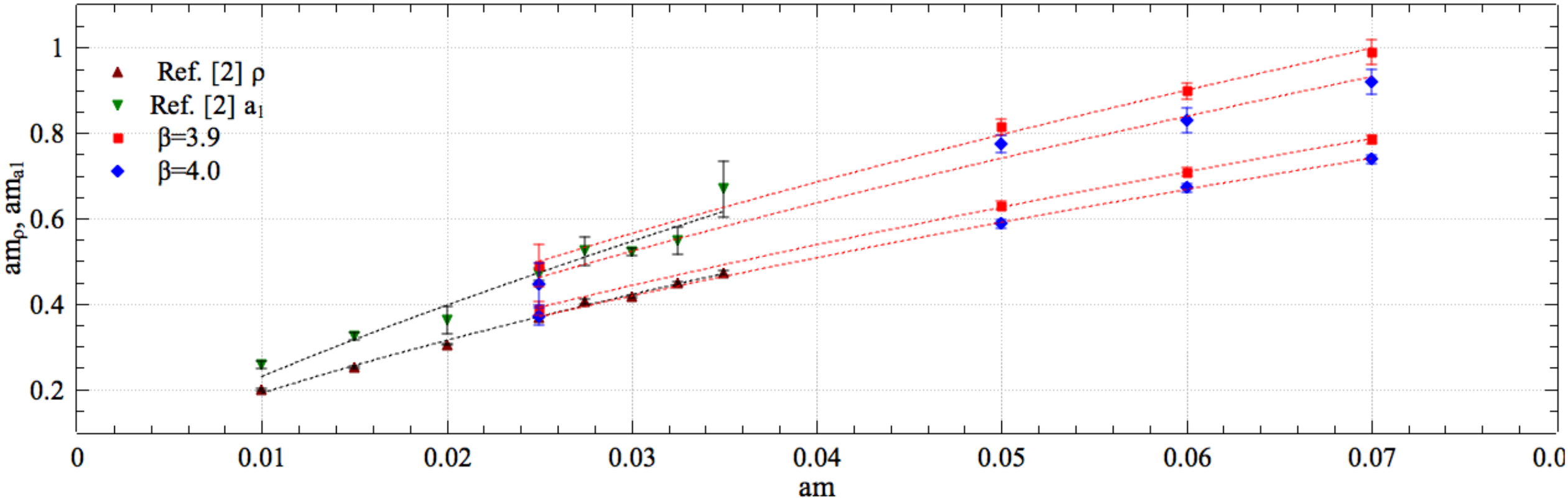
For a fixed m_π/m_ρ the inverted behavior with β_L is compatible with a positive β function

Masses and Power Laws



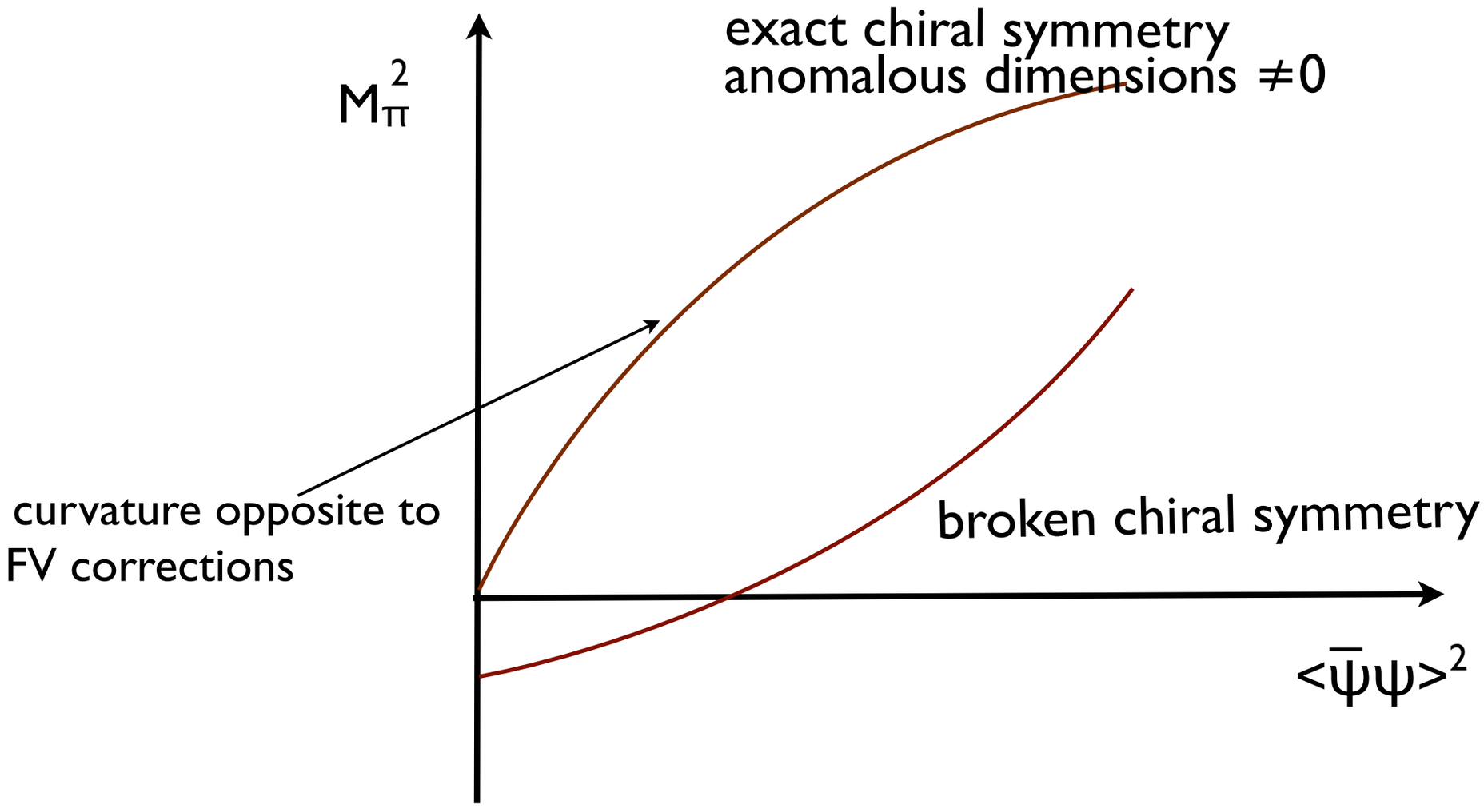
The ratio is approximately constant in a chirally symmetric phase.
It goes to zero in the chiral (massless) limit of QCD.

The axial-vector mass splitting



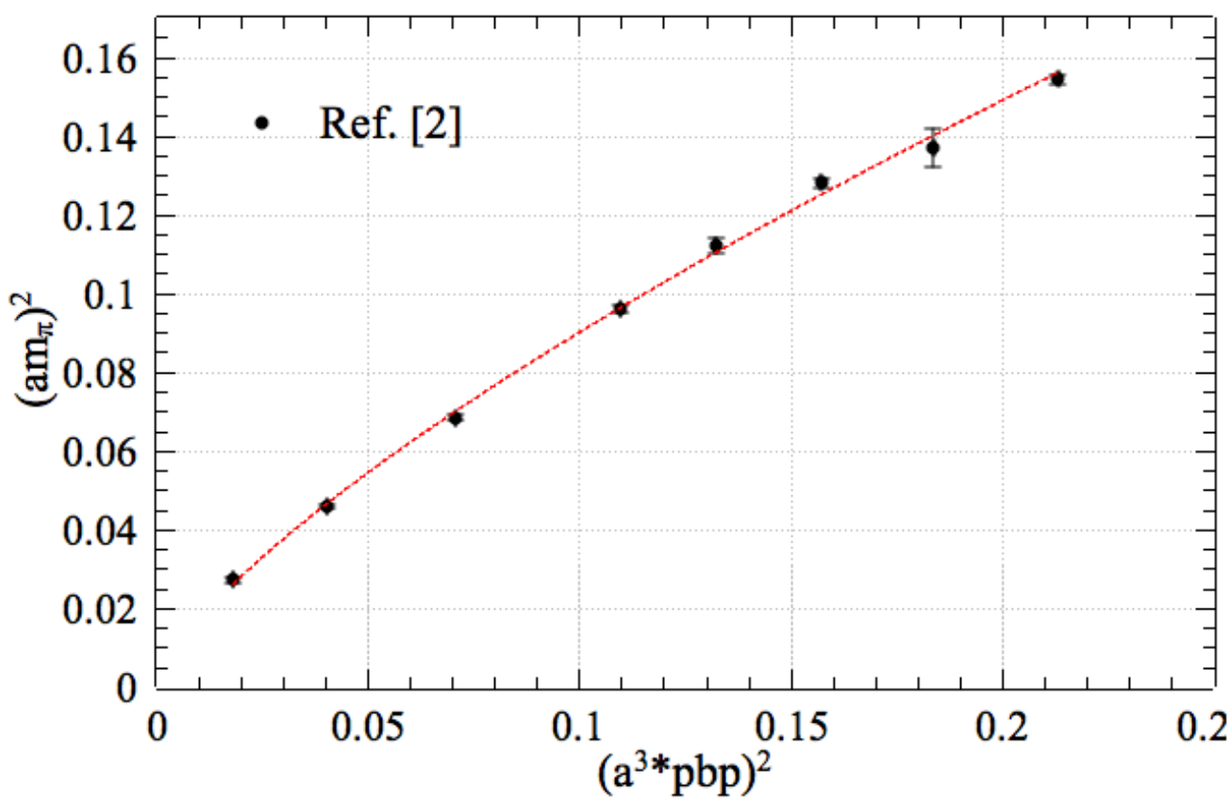
Degeneracy in the chiral (massless) limit signals that chiral symmetry is restored.

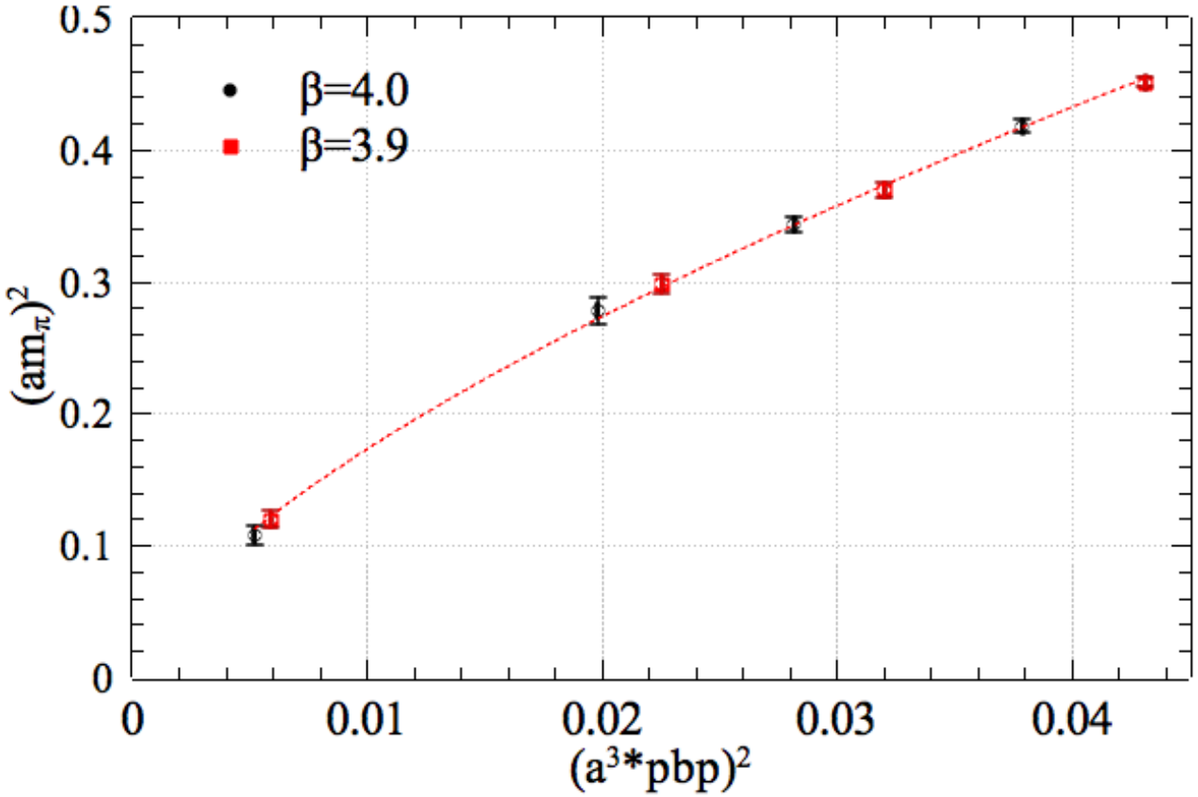
Pseudo Goldstone mass and chiral condensate



Kocic Kogut Lombardo 1993

Nf=12: lattice data





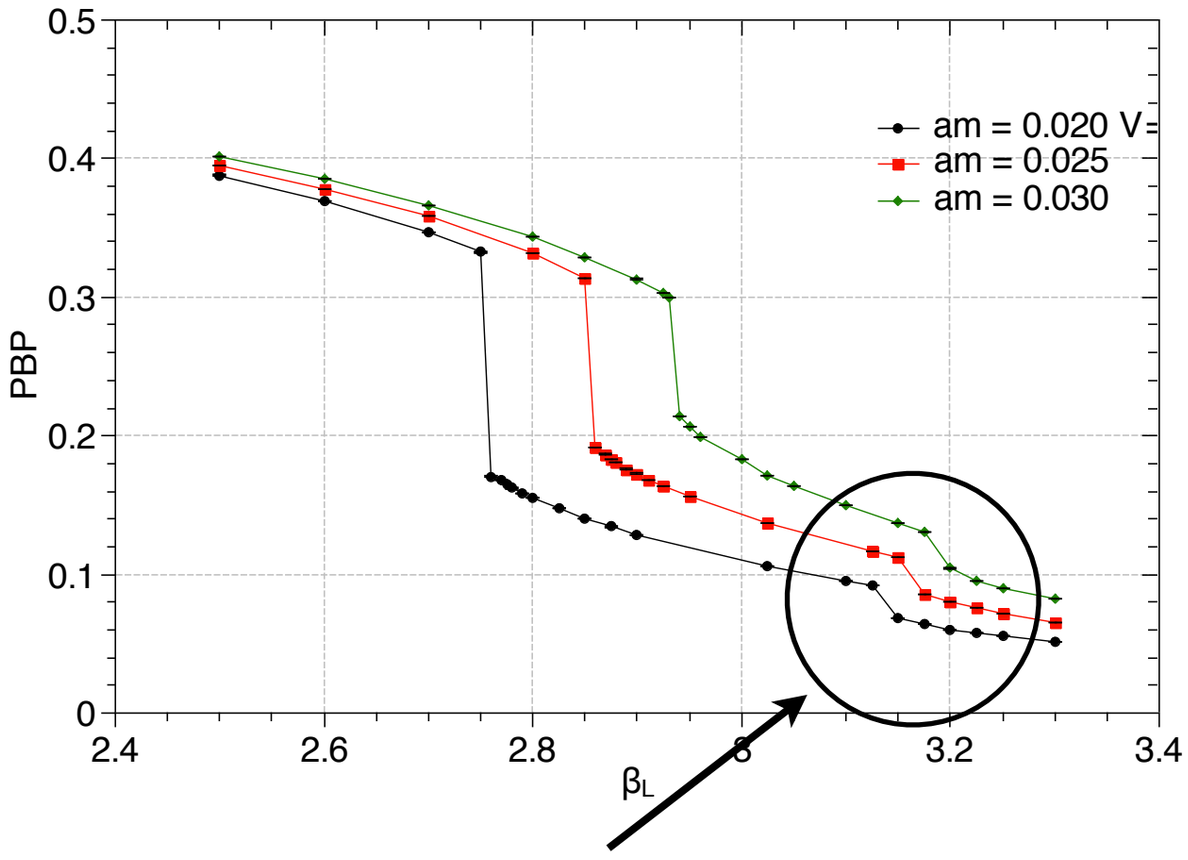
Exact chiral symmetry with non zero anomalous dimensions

Strong coupling (bulk) transitions
and the U(1) axial symmetry

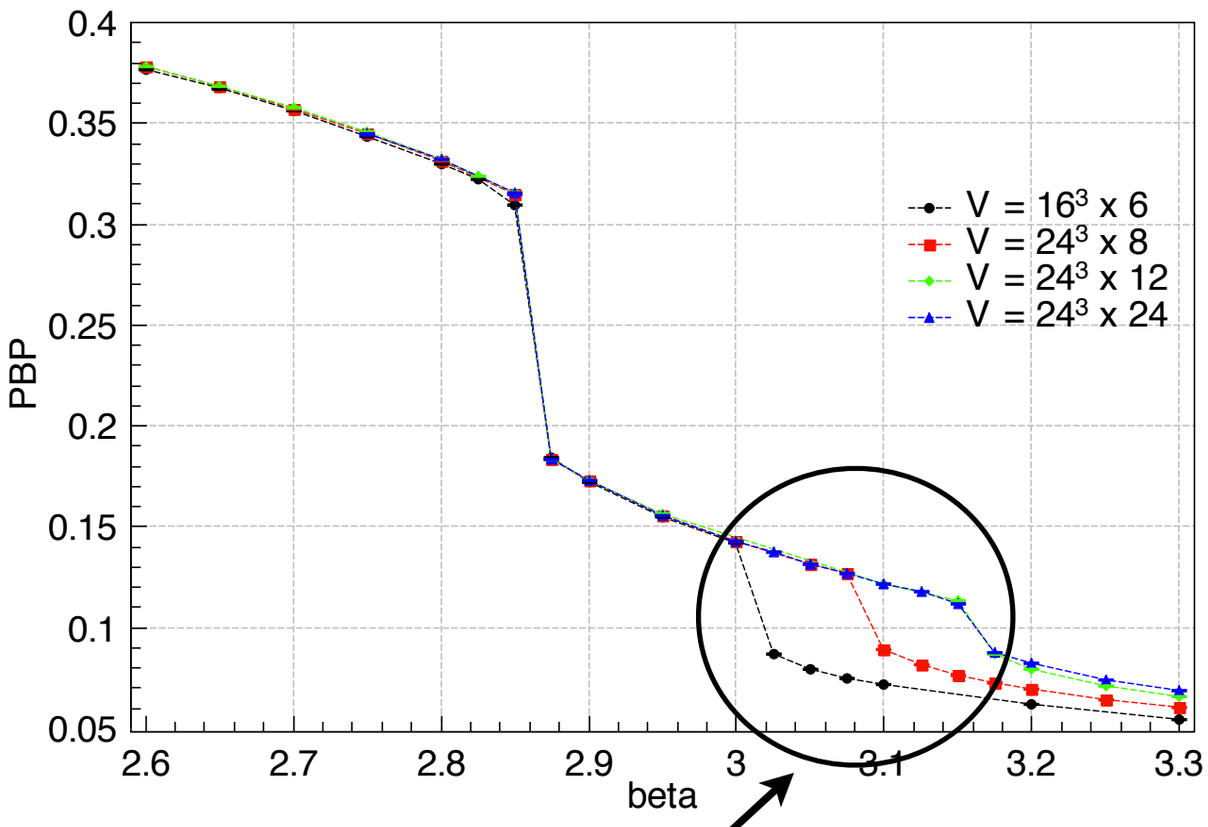
Having already established that there is a bulk transition to a chirally broken phase...
Is it signalling the emergence of a UVFP? Or something else does happen.

The chiral condensate

Lattice fermion action: Naik improved staggered
Lattice gauge action: tree level Symanzik improved
Volumes: 16cx6, 24, 24cx8, 12, 24 (6cx6, 12cx24)
Lattice masses: 0.03, 0.025, 0.02, (0.015)



does not increase
with m decreasing



N_t dependence only for $N_t \leq 12$

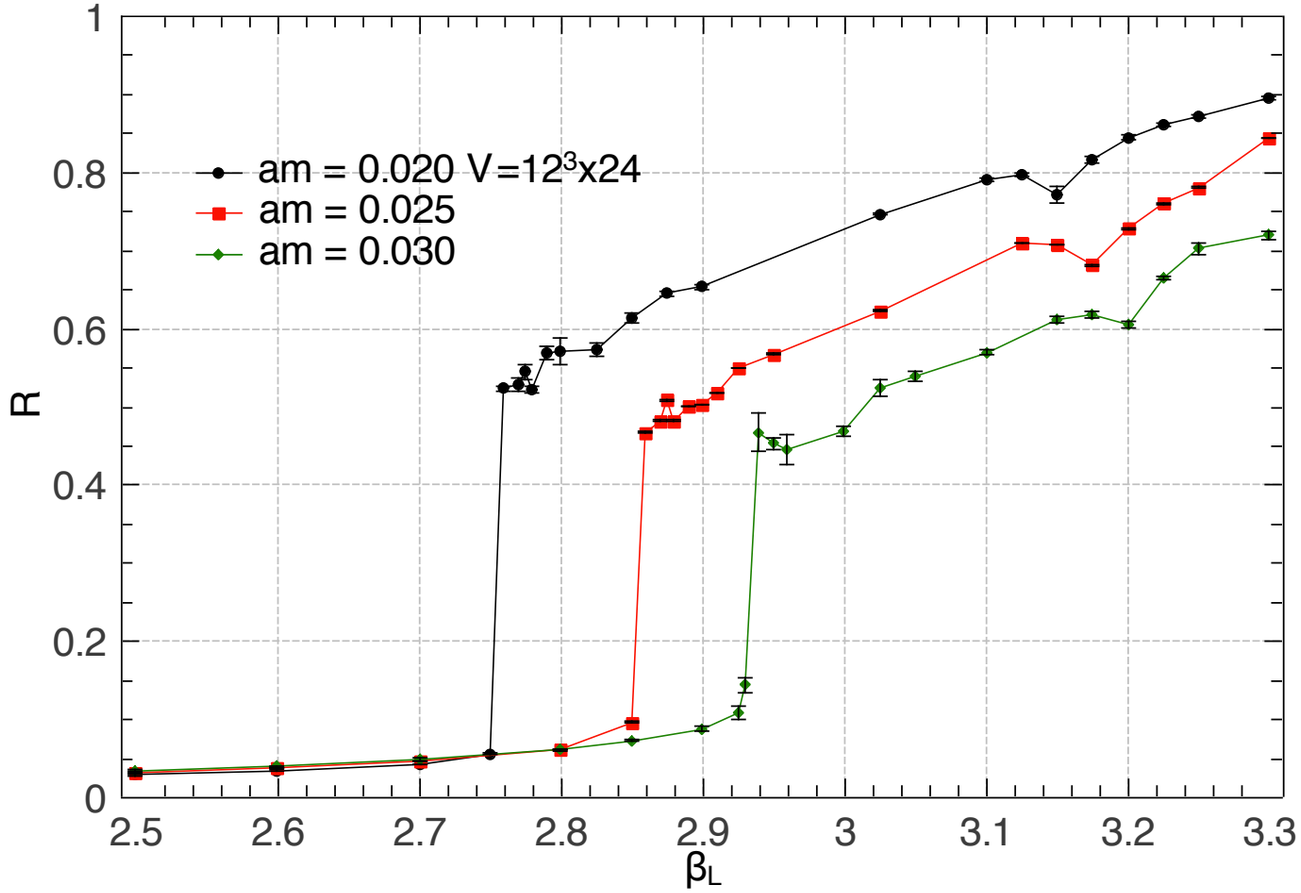
The chiral cumulant

$R = \chi_\pi^{-1}/\chi_\sigma^{-1}$

$\chi_\sigma = \chi_{conn} + \chi_{disc}$

$\chi_\pi = \langle\overline{\psi}\psi\rangle/m$

$M_p^2 = Z_p\, \chi_p^{-1}$



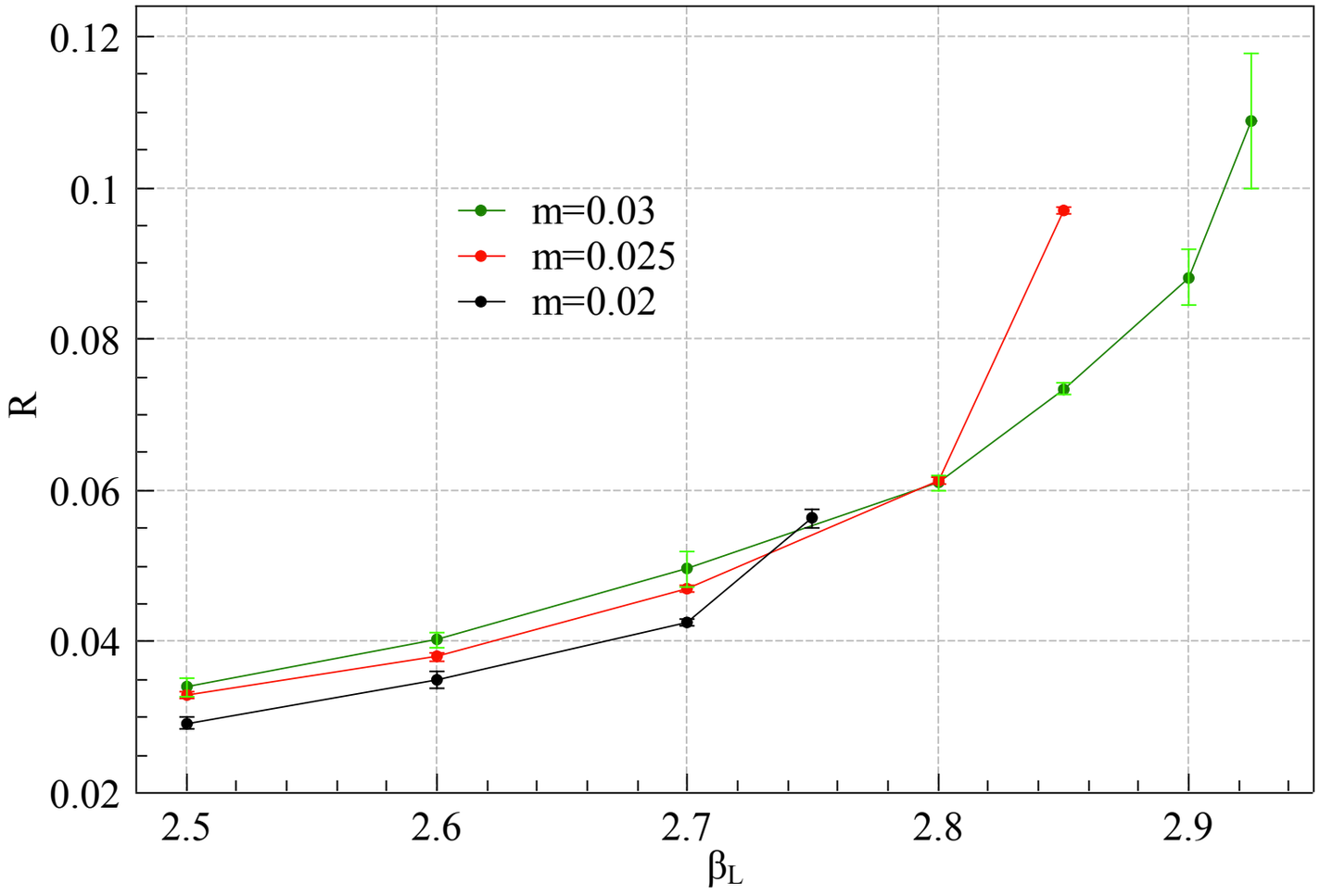
$R \to 1$

π-σ degeneracy

$R \to 0$

π Goldstone

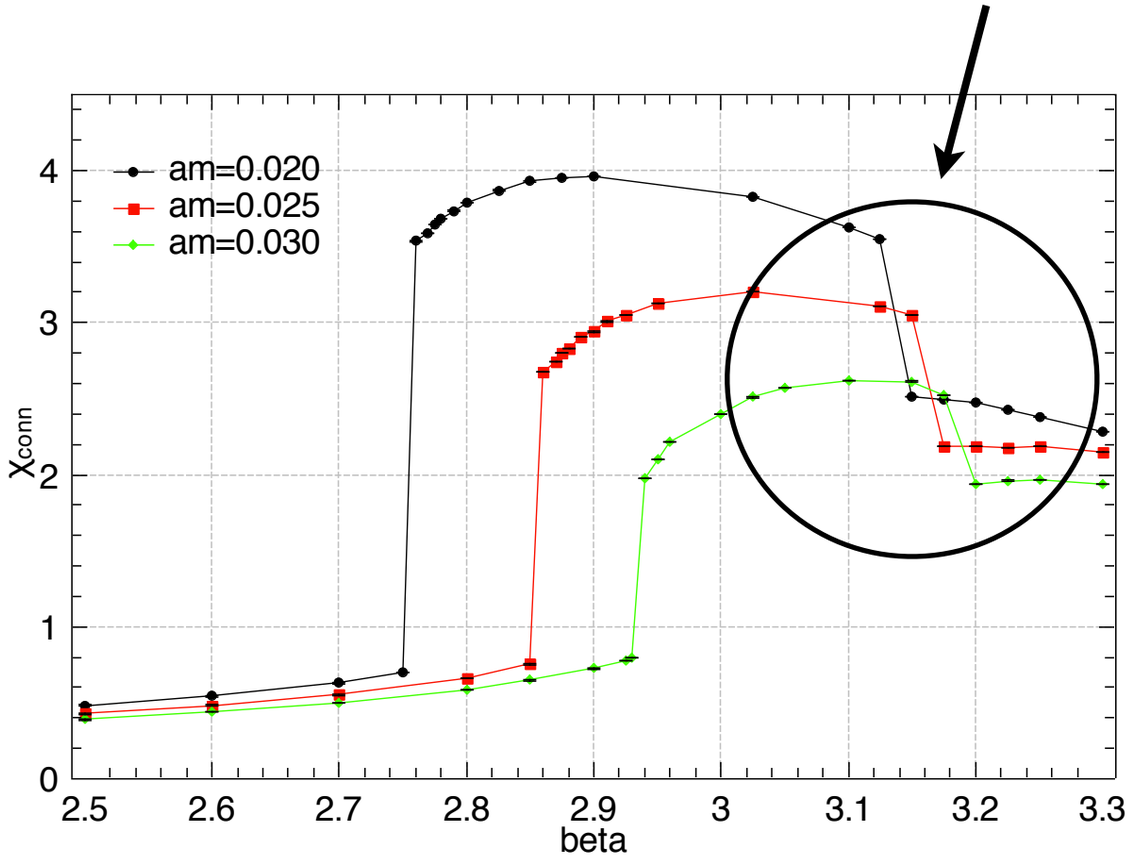
Zoom-in of chiral cumulant

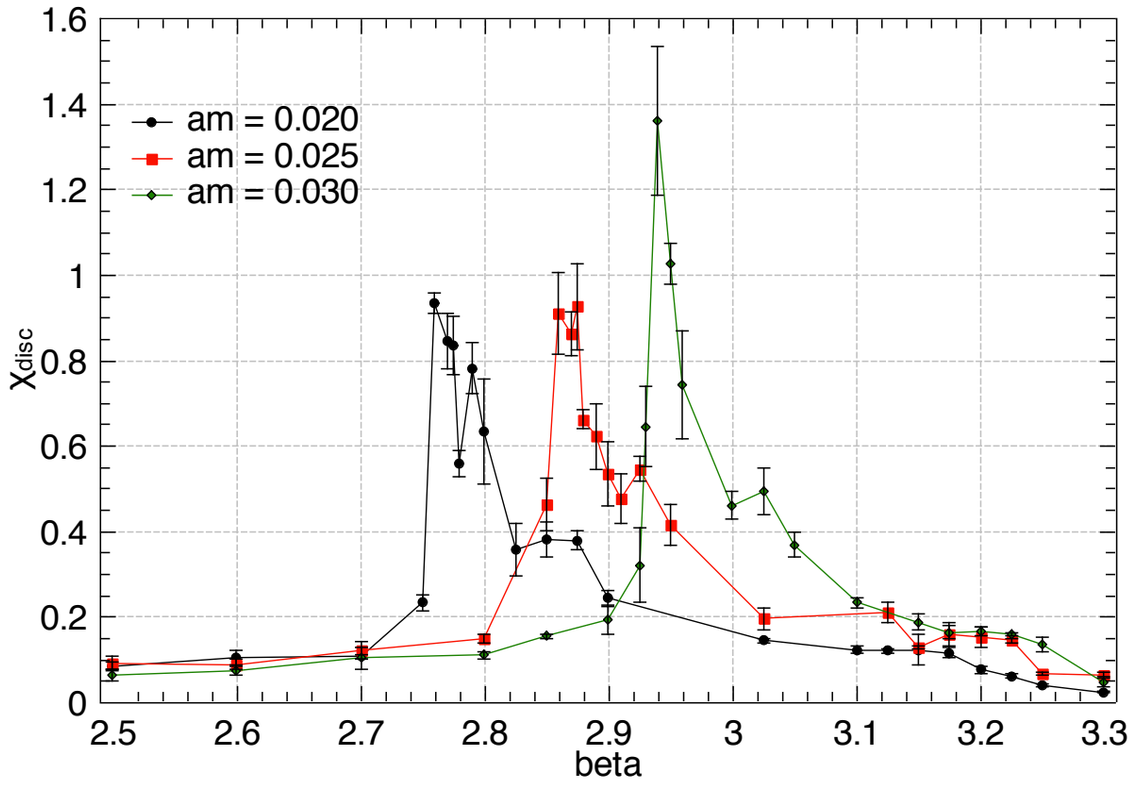


↔

Inversion of mass ordering
at the chiral phase transition

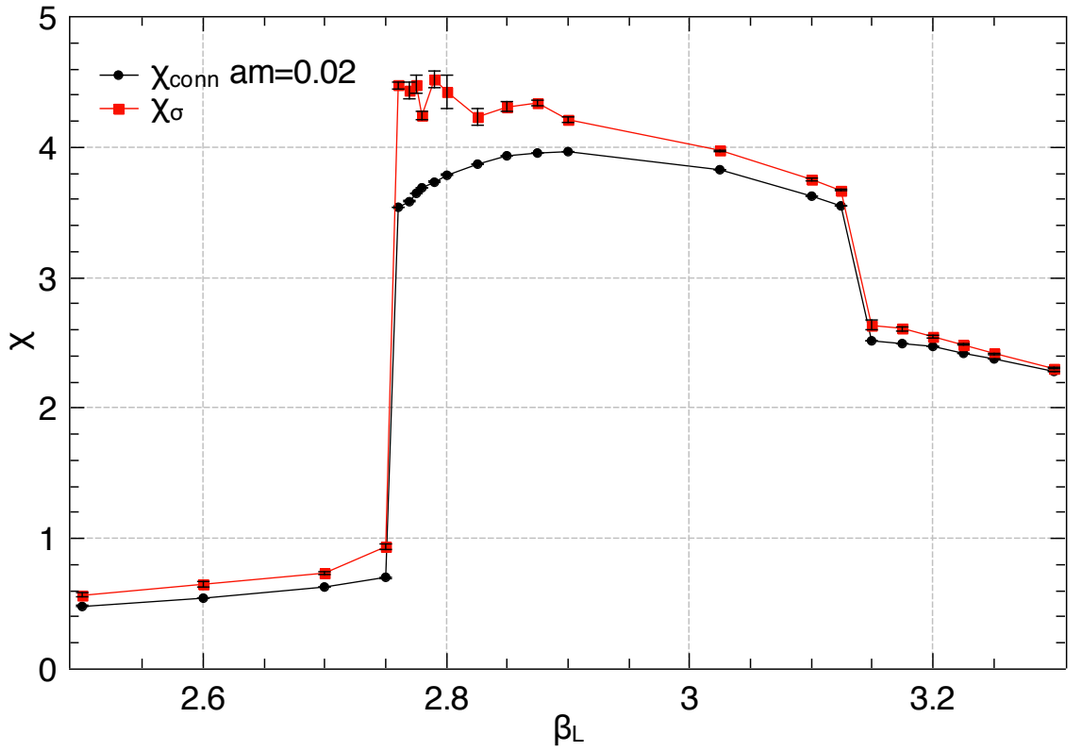
Chiral susceptibilities
mass dependence

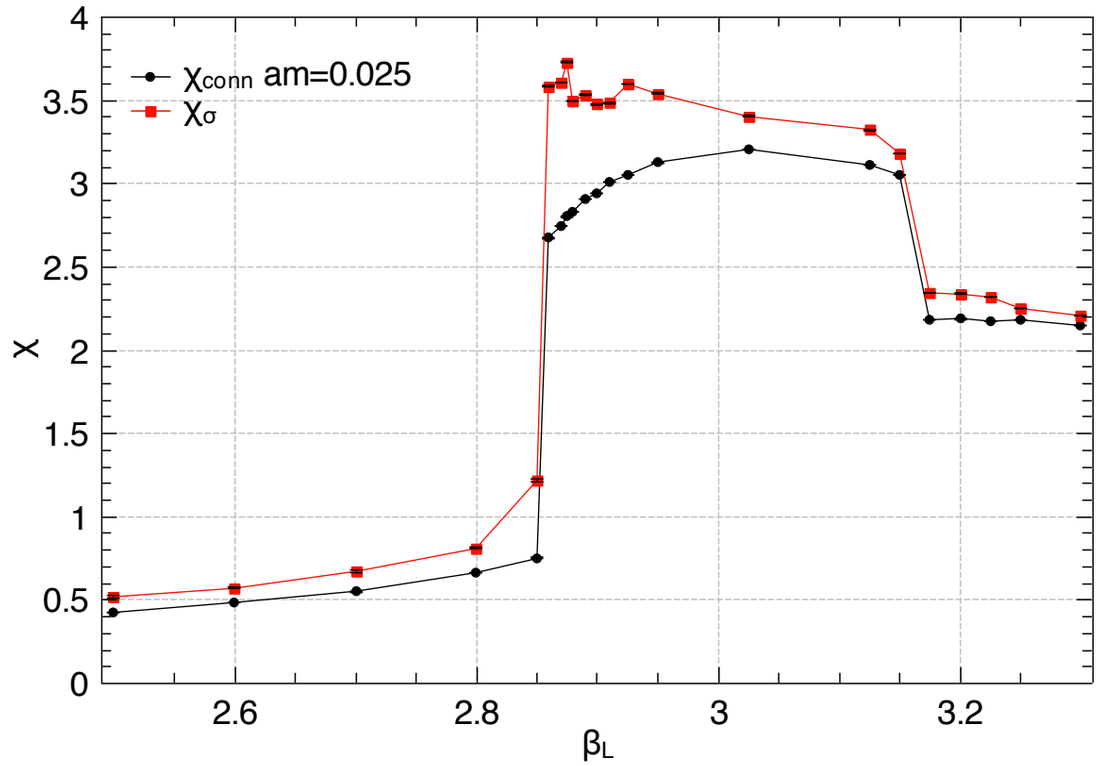




The fate of U(1) axial

Order parameter of U(1) axial





SU(N_f) $\chi_\sigma - \chi_\pi = \chi_{conn} + \chi_{disc} - \chi_\pi \rightarrow$ σ-π degeneracy

$U_A(1)$ $\chi_\delta - \chi_\pi = \chi_{conn} - \chi_\pi \rightarrow$ δ-π degeneracy

Summary: Signatures

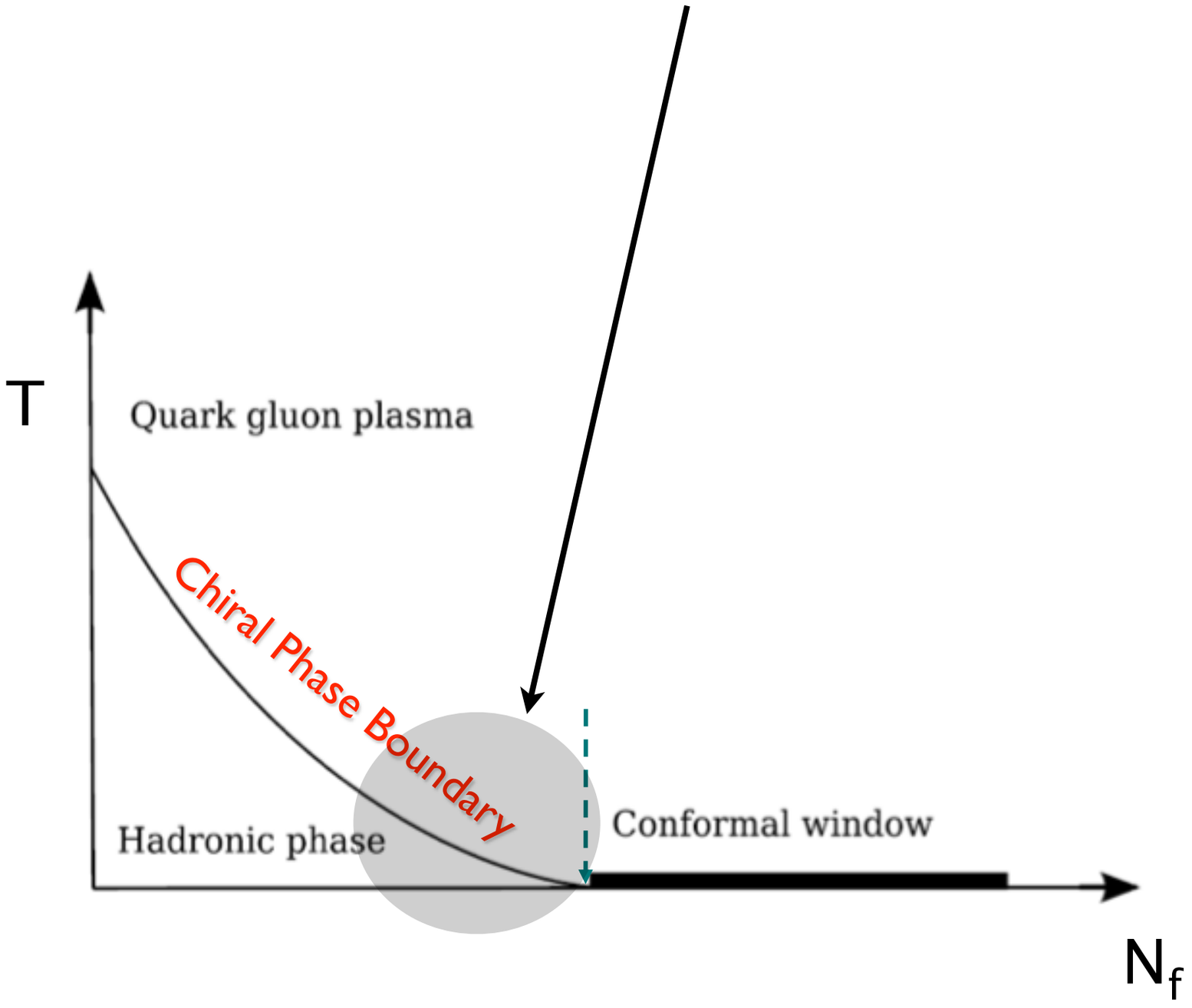
The study of symmetries and related phase transitions in the relevant parameter space provides an ideal tool to explore theories inside and outside the CW.

Inside the CW, the absence of (pseudo) Goldstone bosons generates quite distinctive features as compared with QCD.

It is appealing the possibility that a UVFP at strong coupling emerges inside the CW, in addition to the IRFP. The first order nature of the chiral bulk transition excludes this possibility for Nf=12. However, a UVFP (second order PT) should appear at the end-point of a line of first order PTs --> end-point of the CW.

The appearance of an additional phase at strong coupling is plausibly related to the partial restoration of U(1) axial separately from the SU(Nf) chiral restoration. Additional effects such as an Aoki phase (staggered taste breaking) may add to this.

Preconformal Dynamics


T
Quark gluon plasma
Chiral Phase Boundary
Hadronic phase
Conformal window
N_f

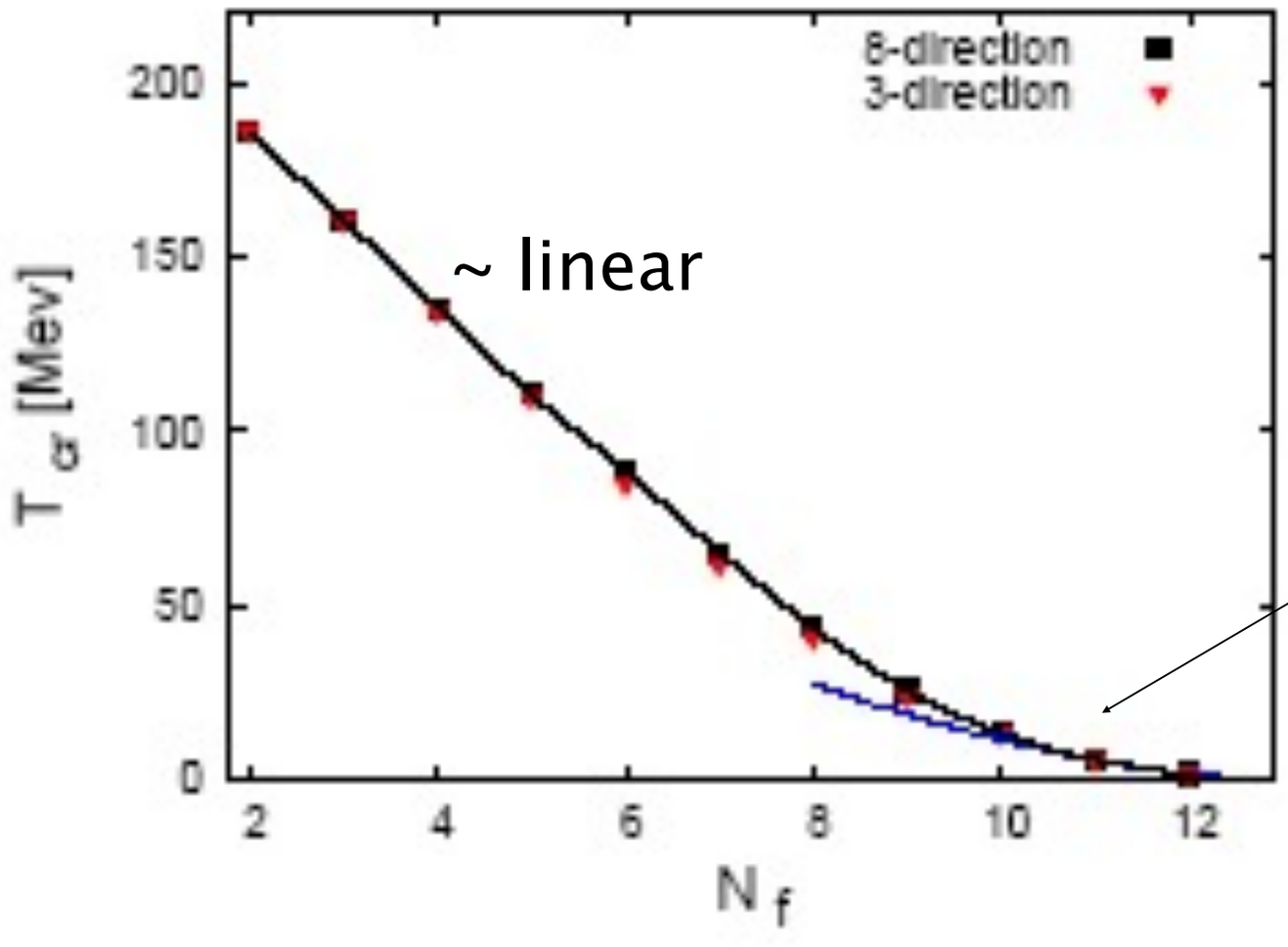
Physics questions

Universal scaling law for the critical Temperature precursor of a conformal phase transition (KBT 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?

The pre-conformal region



$$T_{cr} \sim k_0 \left| N_f - N_f^{cr} \right|^{-1/\Theta}$$

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

Braun, Gies JHEP06 (2006) 024
Braun, Fischer, Gies, arXiv:1012.4279 [hep-ph]

Enhancement of the chiral condensate

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

$\bar\psi\psi$

power-law
(due to running coupling)

exponential-law
(Miransky-KBT scaling)

Lattice results:

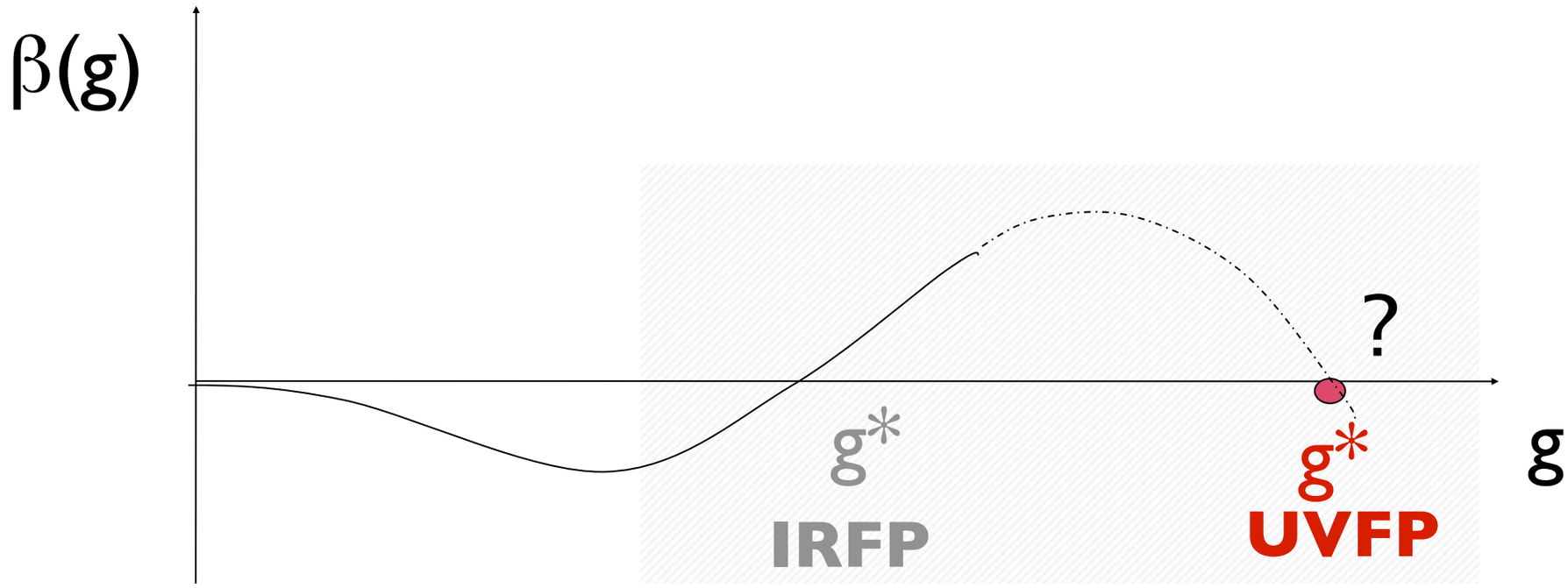
T=0, Nf=6,2 Appelquist et al 2010

T≠0, Nf=0,4,6,8 Miura, Lombardo, EP 2011

AdS/CFT

Disappearance of the CW

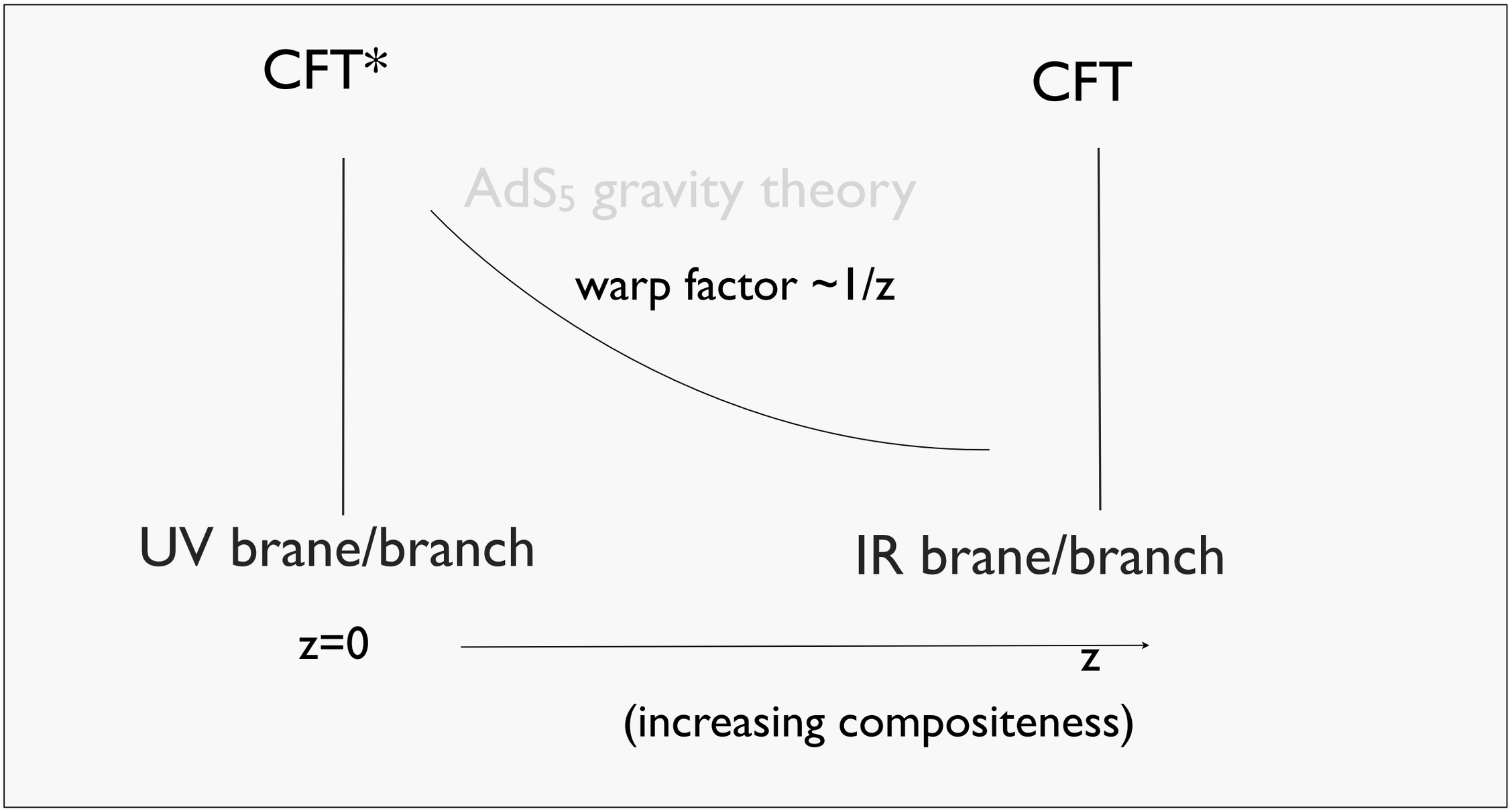
A new viable theory at Strong Coupling?



It suggests the disappearance of conformality via annihilation of a pair of FPs

see Kaplan et al 2009

AdS/CFT



"IR/UV correspondence"

$z \to 0$ IR gravity

$z \to 0$ UV field theory

Duality argument and exact β-function

Seiberg 1995

A conformal window for SQCD must be contained in the region
$3/2\ N_c < N_f < 3N_c$

NSVZ: $$\beta_g = -\frac{g^3}{16\pi^2}\ \frac{3N_c - N_f(1-\gamma_0)}{1-\frac{g^2 N_c}{8\pi^2}}$$

FPs merging in "modified" SQCD?

Found a gravity solution that reproduces the NSVZ β-function of $\mathcal{N}$=1 SYM and confinement Maldacena, Nunez 2004

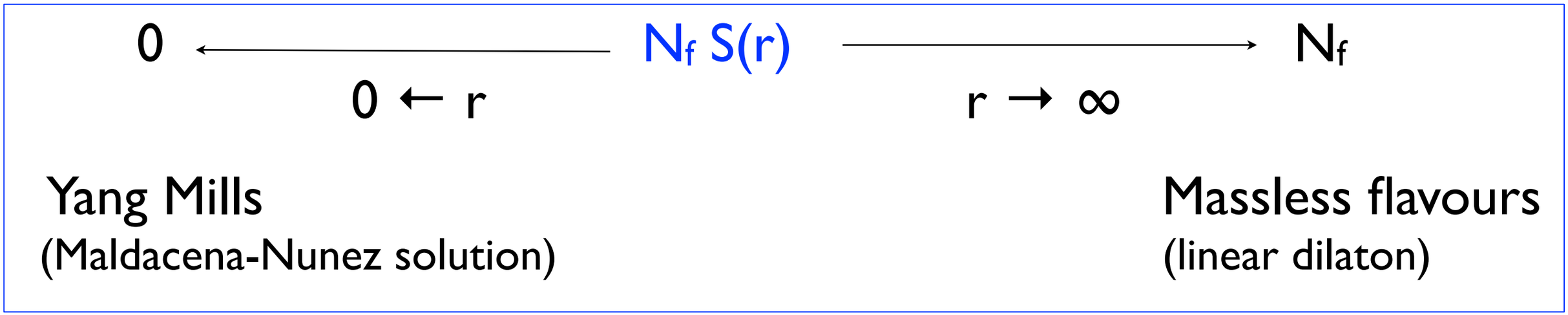
Towards SQCD (large N_f, N_c: N_f/N_c fixed): SUGRA backgrounds

Massless case Casero Nunez Paredes 2008

Massive case (smooth interpolation) Conte Gaillard Ramallo 2011

⇒ SQCD + quartic operators

Mass interpolating function



The β-function from AdS/CFT

Ingredients: gravity solution - gauge coupling relation
energy - radius relation

Limitations: (gravity) singularities ($r \to 0$)

Recent results: Barranco EP Russo 2011

$N_f < 2N_c$ 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 ($N_c \to N_f\text{-}N_c$, $N_f\text{-}2N_c$ flips sign)

Summary

Strongly coupled (quasi)conformal gauge theories play a role in the physics of QGP and might play a role in particle physics at and above the EWSB scale.

Large-Nf QCD is an instructive theory playground

✓ The conformal window opens around $N_f \sim 12$
✓ The spectrum and phase transitions provide distinctive signatures of (pre)conformality

AdS/CFT suggests a unified view where 4D theories of particle physics are dual to gravity theories in AdS_5

➡ AdS/CFT in phenomenology: warped RS1 models
➡ AdS/CFT as a mathematical tool: FPs merging?

A UVFP is found at strong coupling for $N_f=2N_c$ in a class of gravity solutions dual to SQCD plus higher dimensional operators.