Phases of QCD, topology and axions - II

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I Symmetries and phases
of QCD in the
Temperature, Nf space

II Results on the phase diagram

III Topology - broken phase

IV Topology - hot QCD & axions

II Results on the phase diagram

II.1 The magnetic EoS
at finite temperature.

II.2 The conformal phase

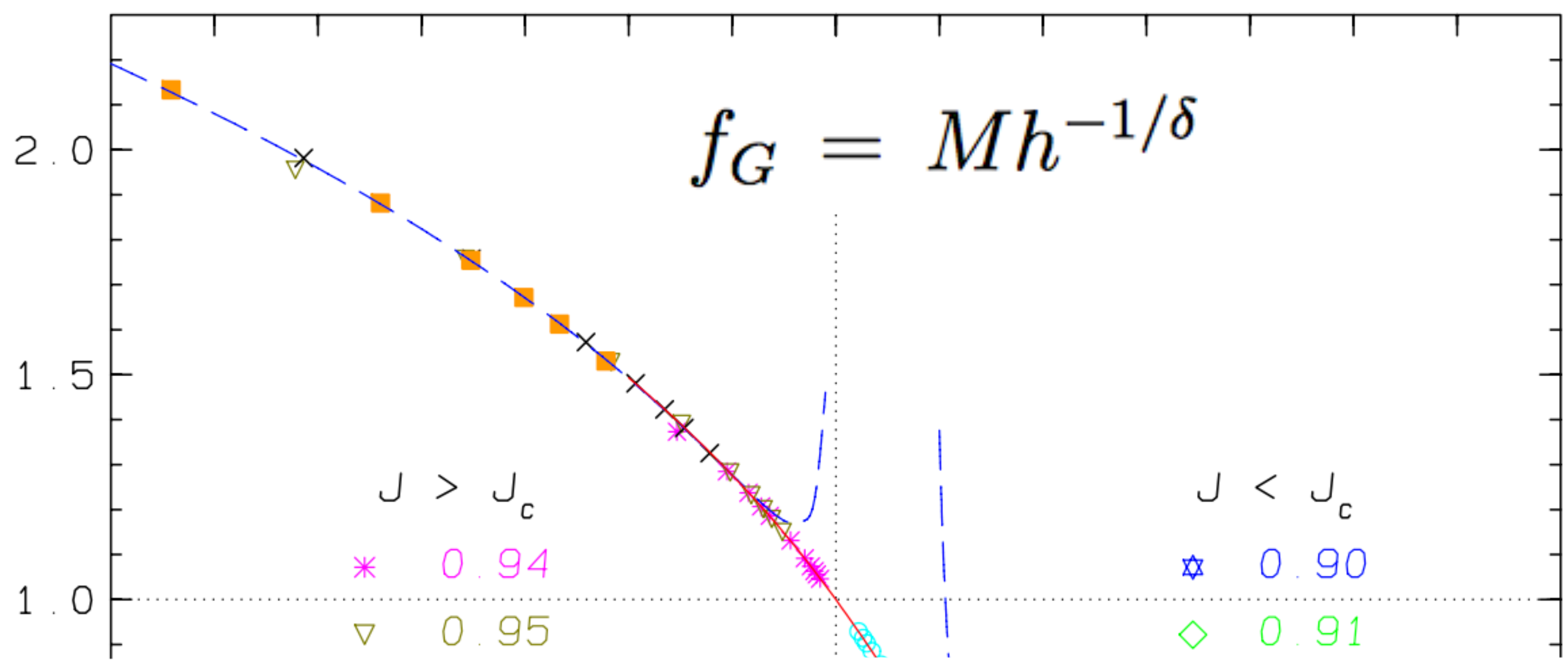
II.3 The preconformal phase

II.1 Magnetic EoS in QCD at finite temperature

3d O(4) model

$$\beta \mathcal{H} = -J \sum_{<\vec{x},\vec{y}>} \vec{\phi}_{\vec{x}} \cdot \vec{\phi}_{\vec{y}} - \vec{H} \cdot \sum_{\vec{x}} \vec{\phi}_{\vec{x}}$$

$$M = h^{1/\delta} f_G(z)$$



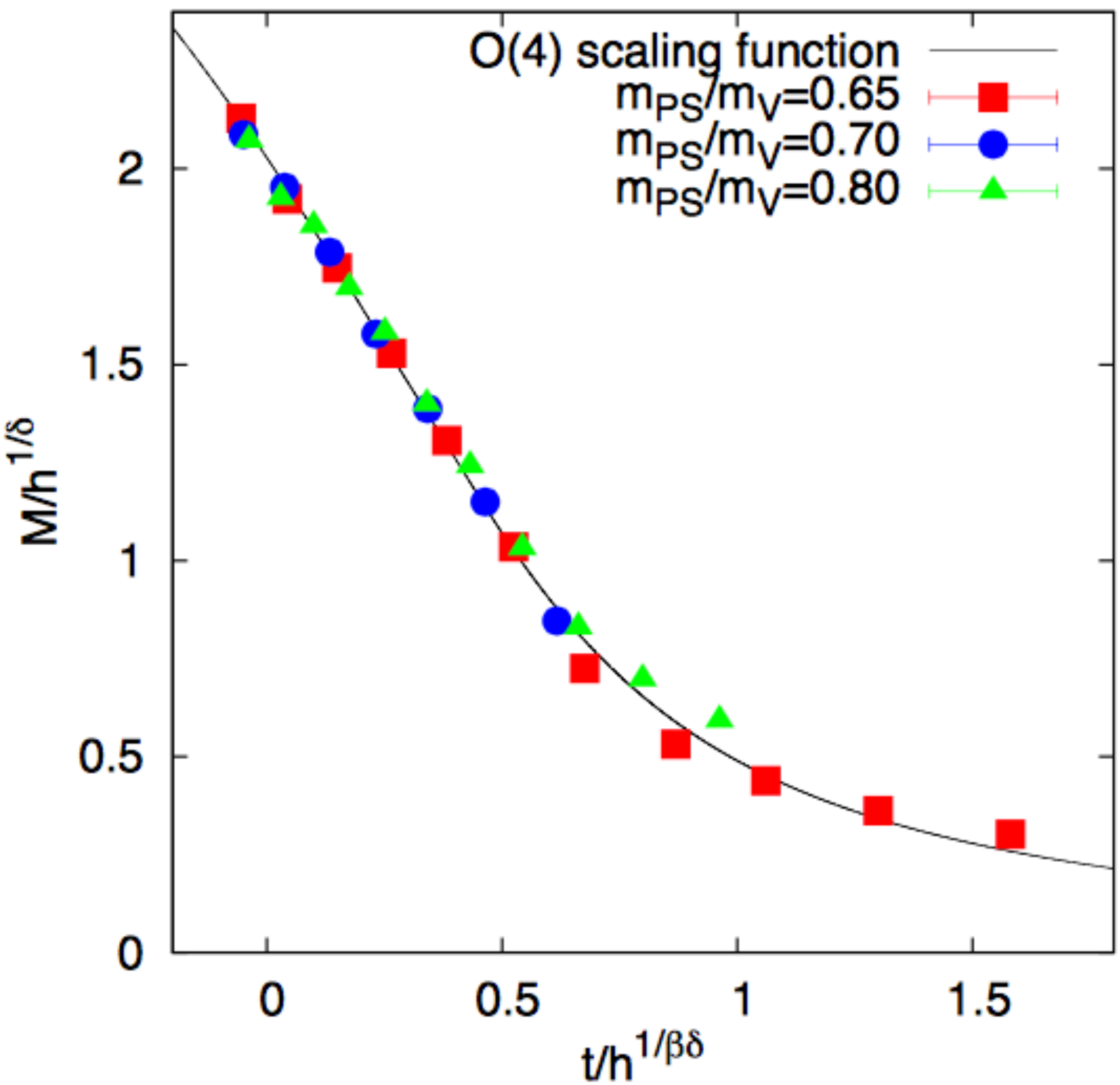
Building& parametrizing the scaling function *f(z)*

Karsch Engels 2012

$$z = \bar{t}/h^{1/\Delta} \qquad \Delta \equiv \beta\delta$$

O(4) scaling analysis in two-flavor QCD at finite temperature and density with improved Wilson quarks

Umeda et al. 2017

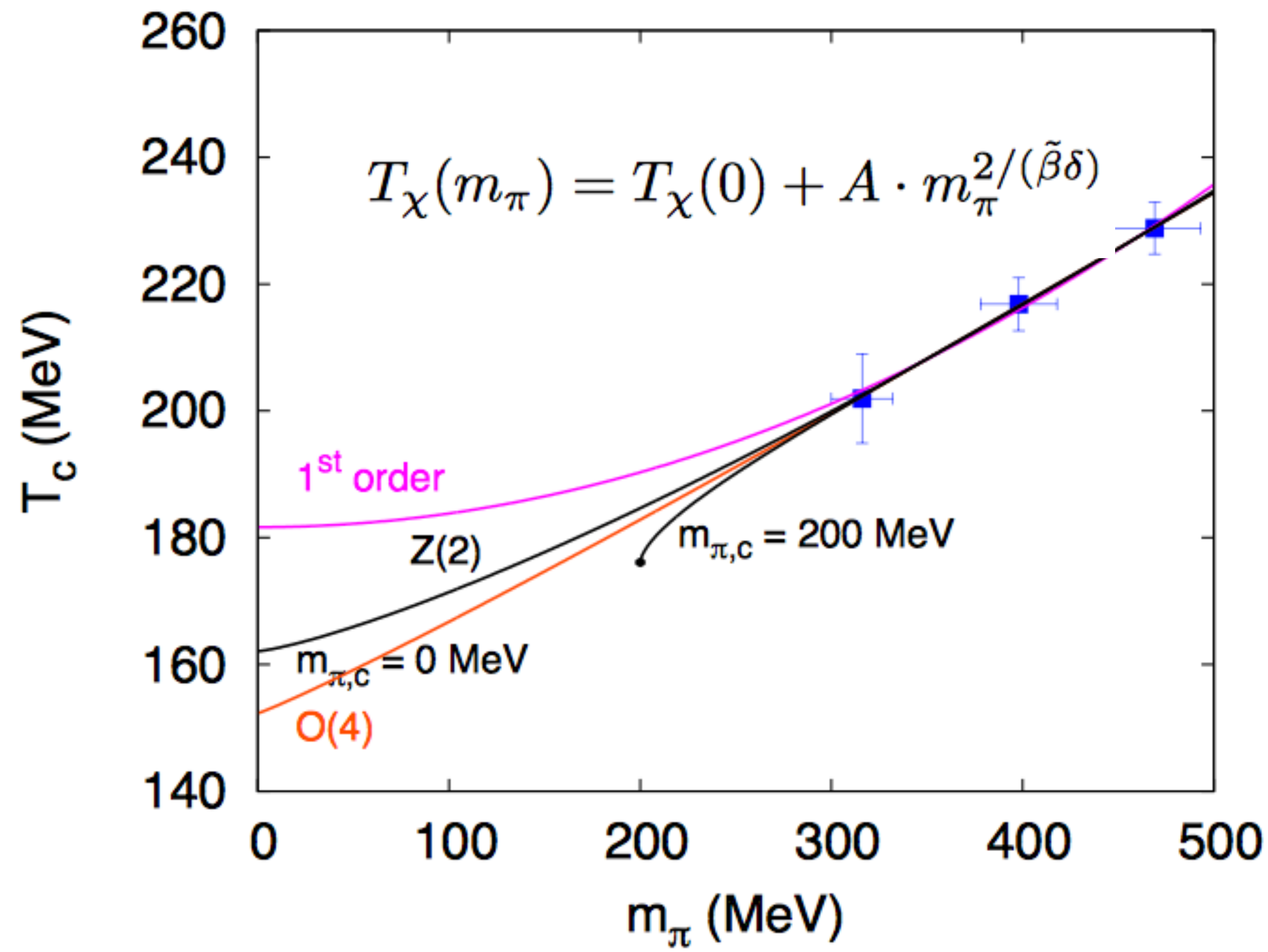


Apparently nice O(4) scaling for the order parameter

$$M/h^{1/\delta} = f(t/h^{1/\beta\delta})$$

Twisted mass
at finite temperature
collaboration,
Nf=2

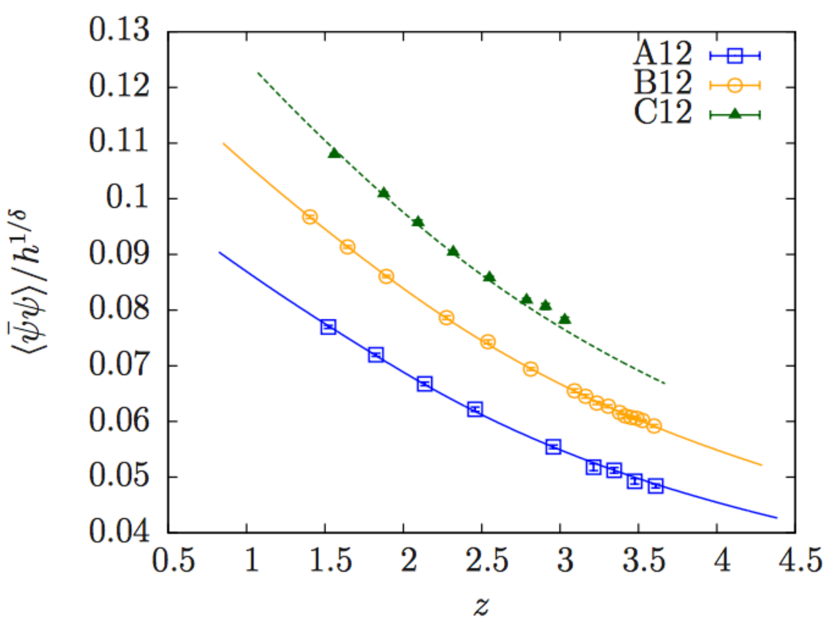
Hard to discriminate
between different
univ. classes



gives
scaling
of

$$T_\chi(m_\pi)$$

Chiral extrapolation for $T_\chi(m_\pi)$ for various scenarios



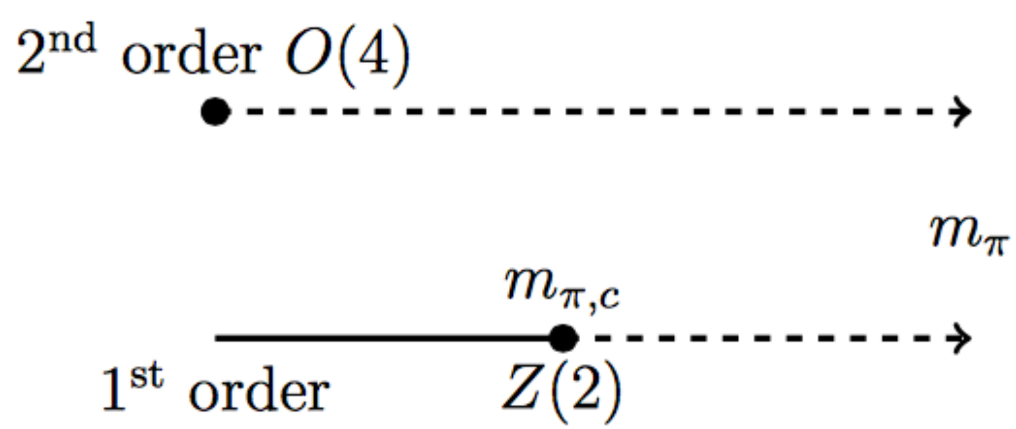
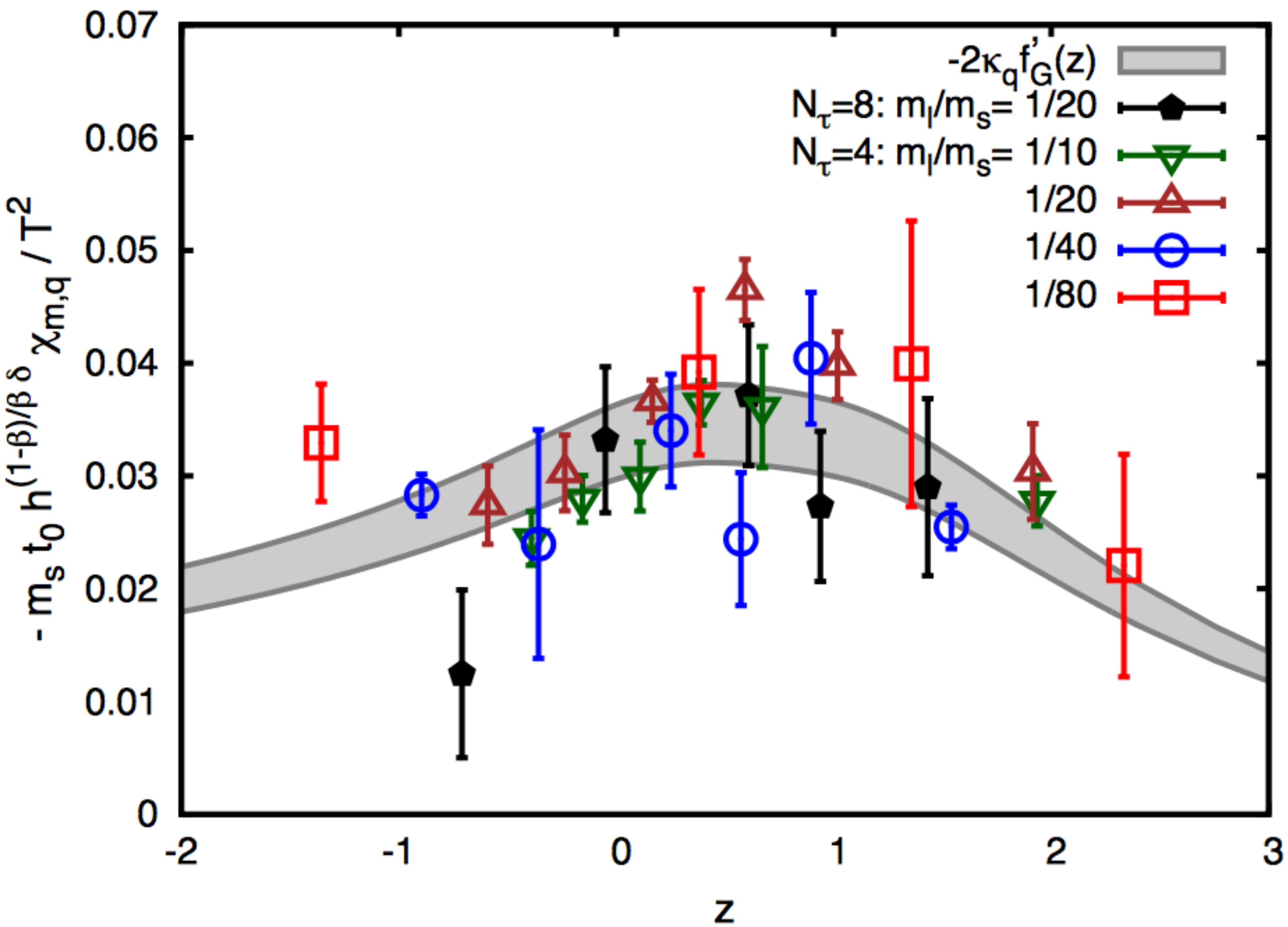


Illustration of possible scenarios for the $N_f = 2$ chiral limit.

Phase boundary for the chiral transition in (2+1) -flavor QCD at small values of the chemical potential

O. Kaczmarek et al. 2011



The EoS extended at finite μ

$$\frac{T_c(\mu_q)}{T_c} = 1 - \kappa_q \left(\frac{\mu_q}{T}\right)^2 + \mathcal{O}\left(\left(\frac{\mu_q}{T}\right)^4\right)$$

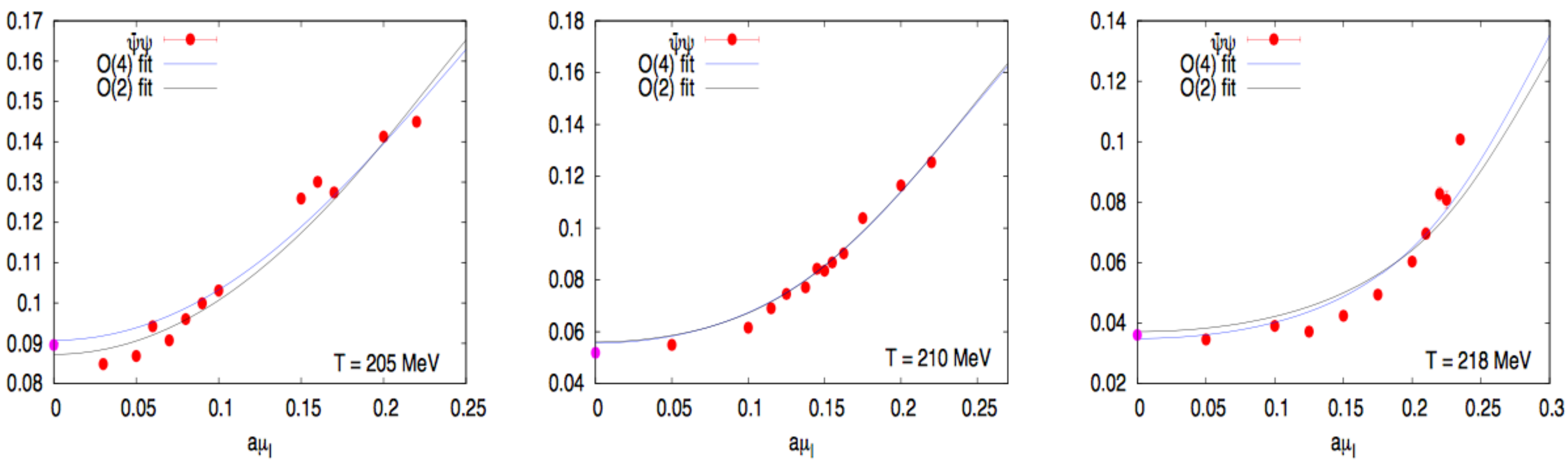
determines slope of the critical line

$$\frac{\chi_{m,q}}{T} = \frac{2\kappa_q T}{t_0 m_s} h^{-(1-\beta)/\beta\delta} f'_G(z) .$$

Making the most of Taylor expansion and imaginary μ

Same strategy may be used at imaginary μ

Laermann, Meyer, MpL 2013



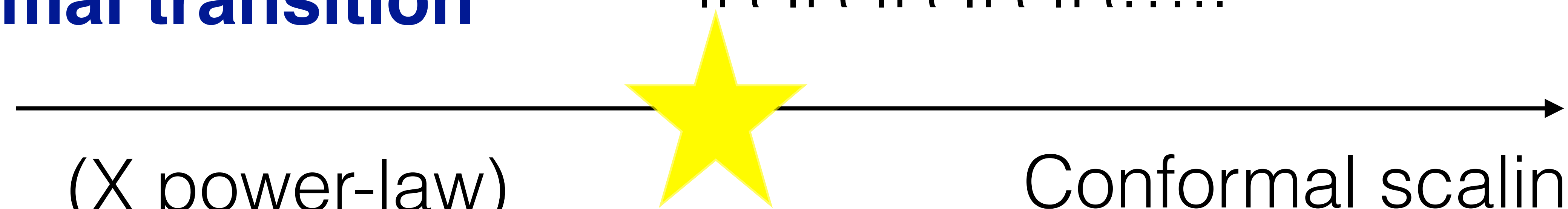
within largish error, either O(2) and O(4) universality classes nicely describe the data and allow an estimate of the slope.

II.2 Establishing the conformal window

Similarities and differences between a conformal PT and a 2nd order one

Conformal transition

IR IR IR IR IR.....



(X power-law)

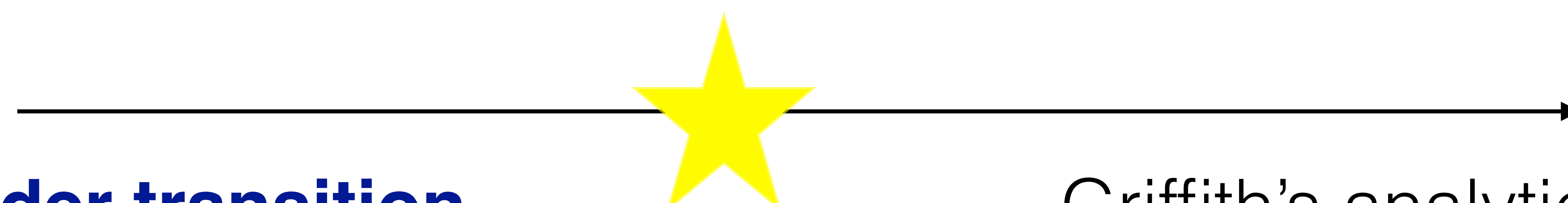
Conformal scaling

Analogies
in the broken phase

Differences
in the symmetric phase

EoS

IR

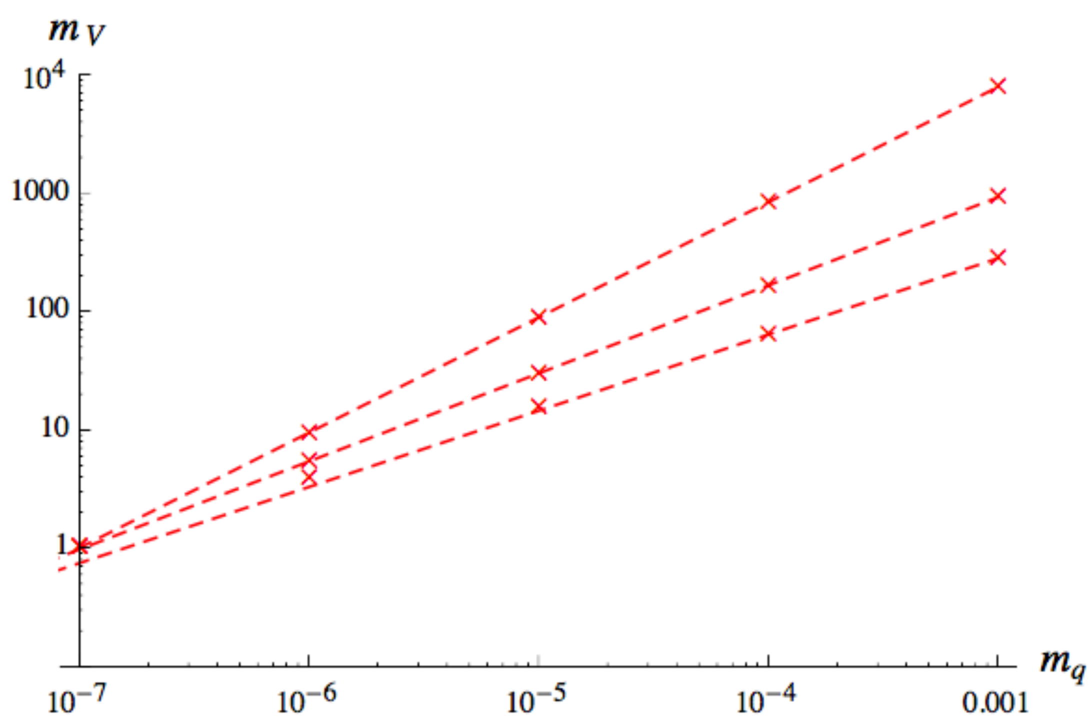


2nd order transition

Griffith's analyticity

Conformal scaling

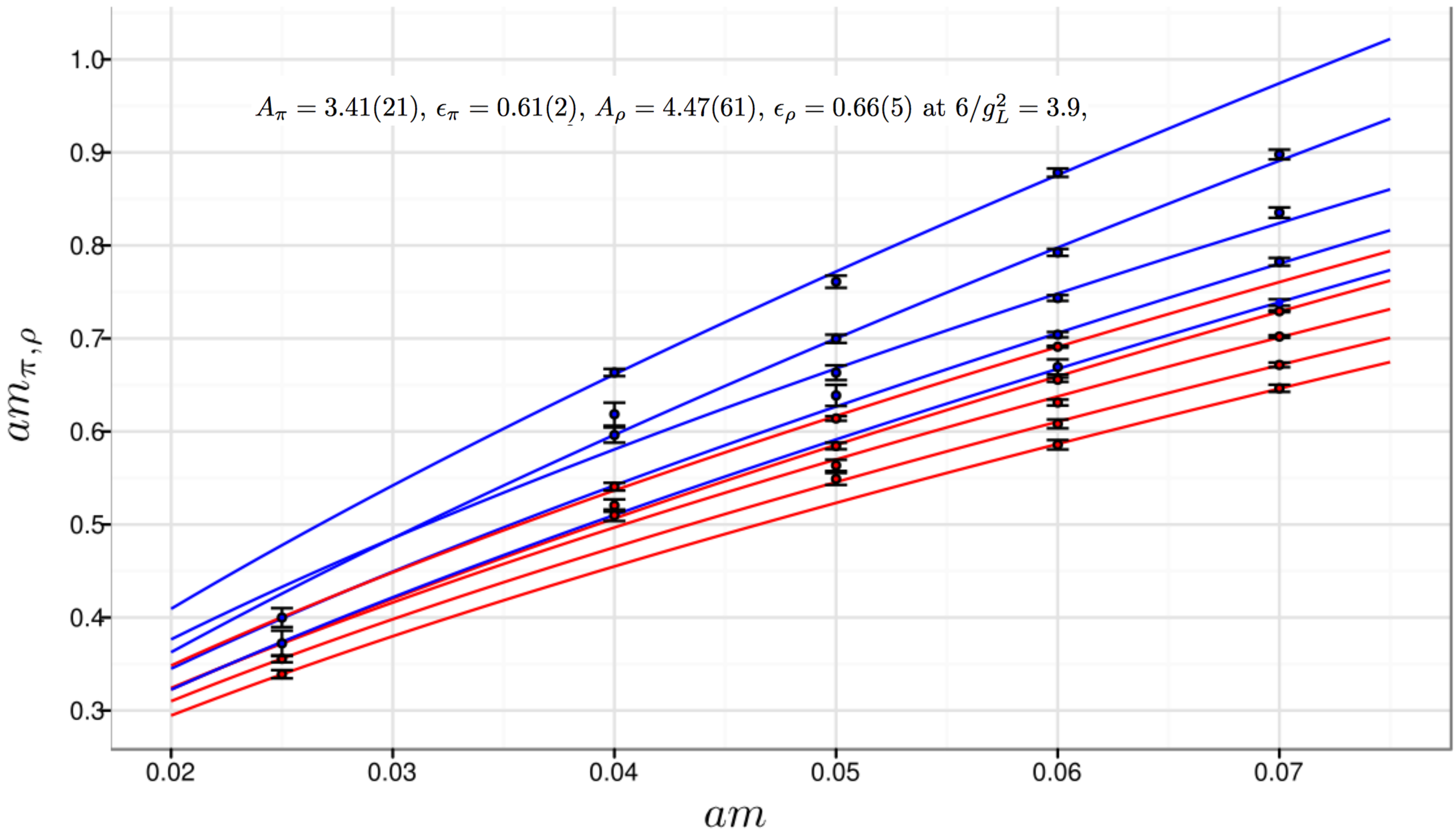
$$M_H = c_H m^{1/y_h}$$



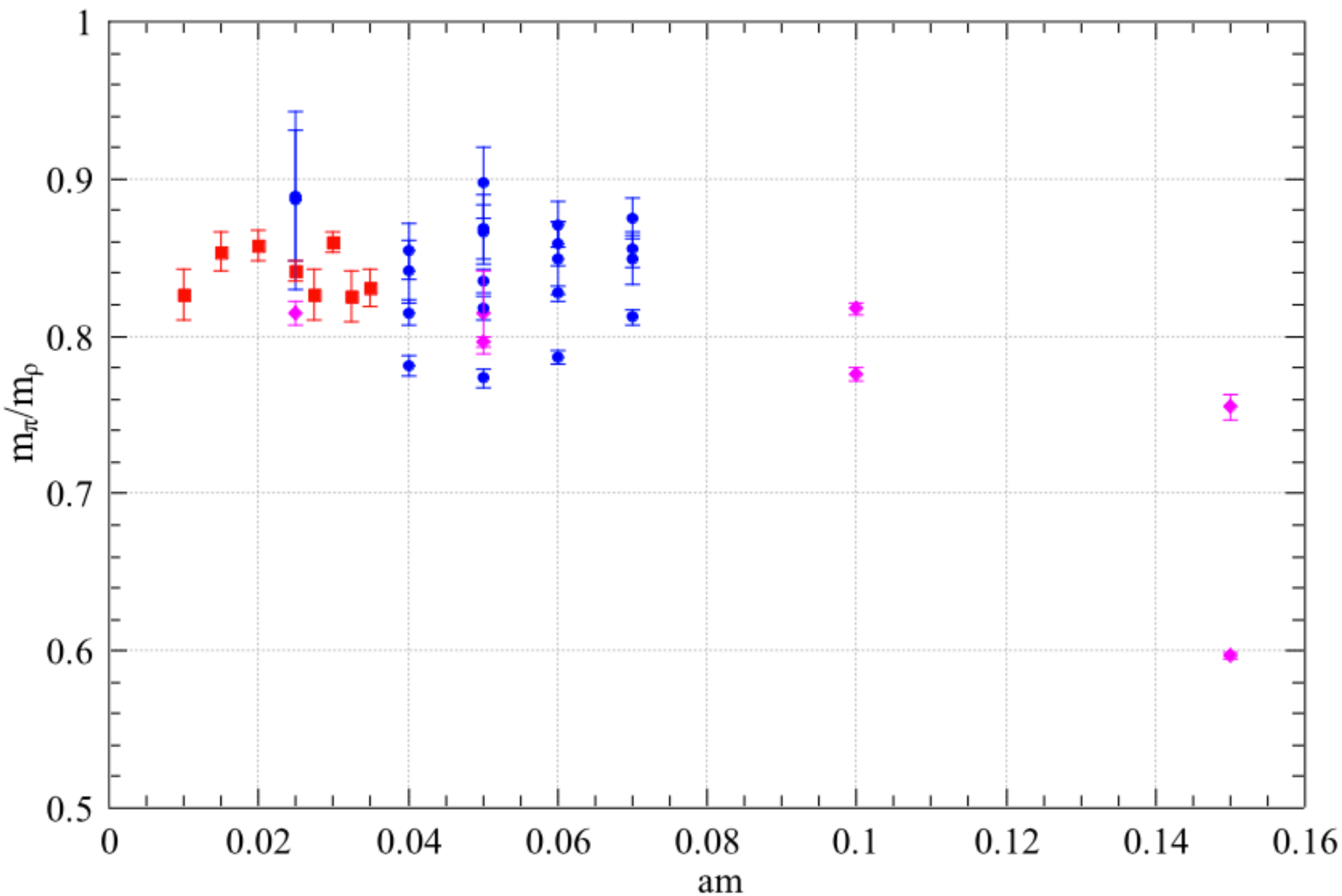
Power law Scaling with
anomalous dimension

Alho Evans Tuominen 2014

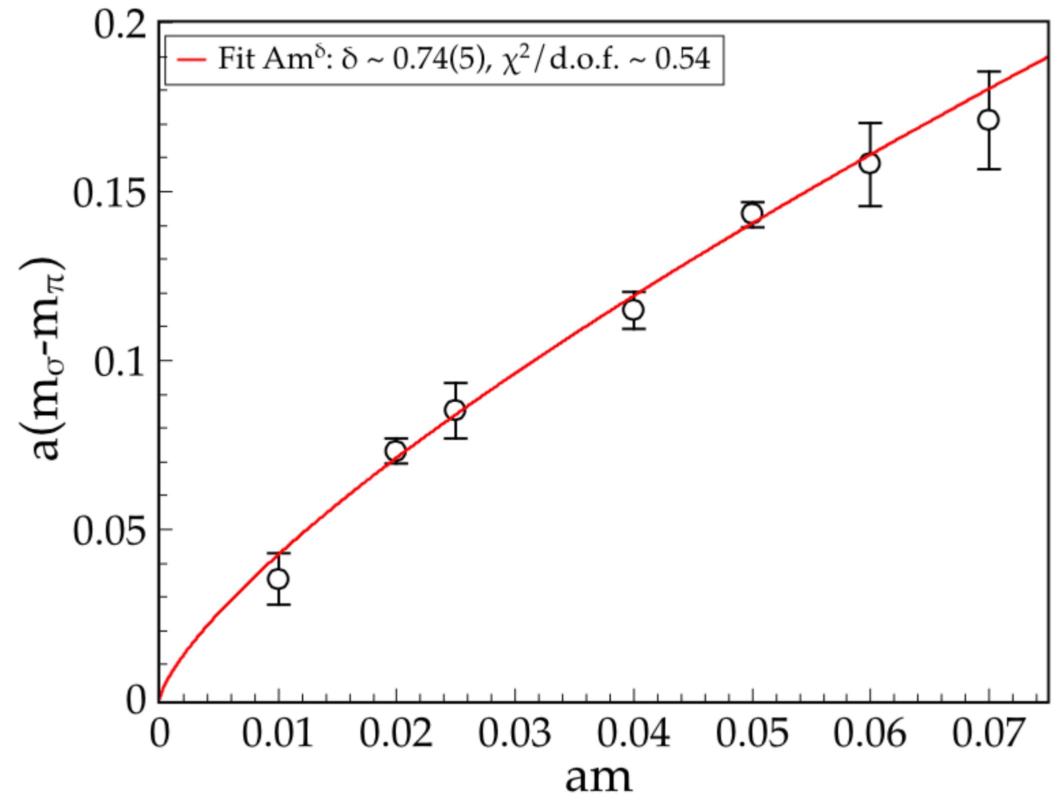
$$m_{\pi,\rho} = A_{\pi,\rho} m^{\epsilon_{\pi,\rho}}$$

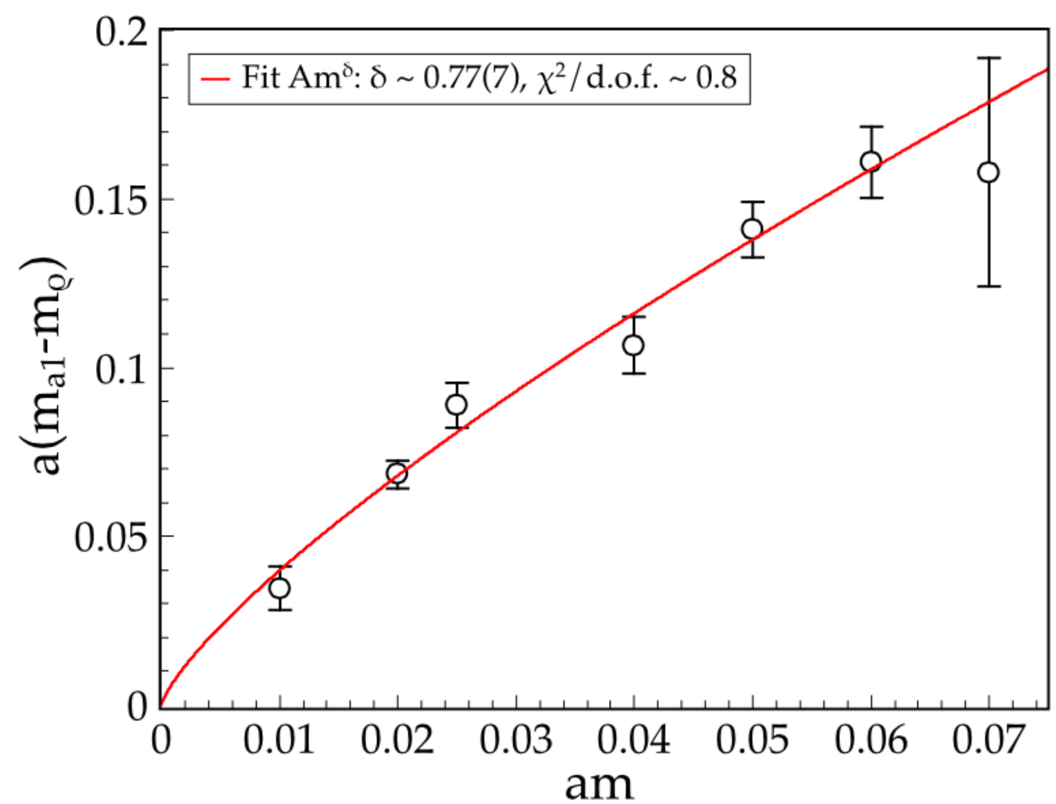


$m_{\pi,\rho} = A_{\pi,\rho} m^{\epsilon_{\pi,\rho}}$: mass ratios m-independent in the chiral limit



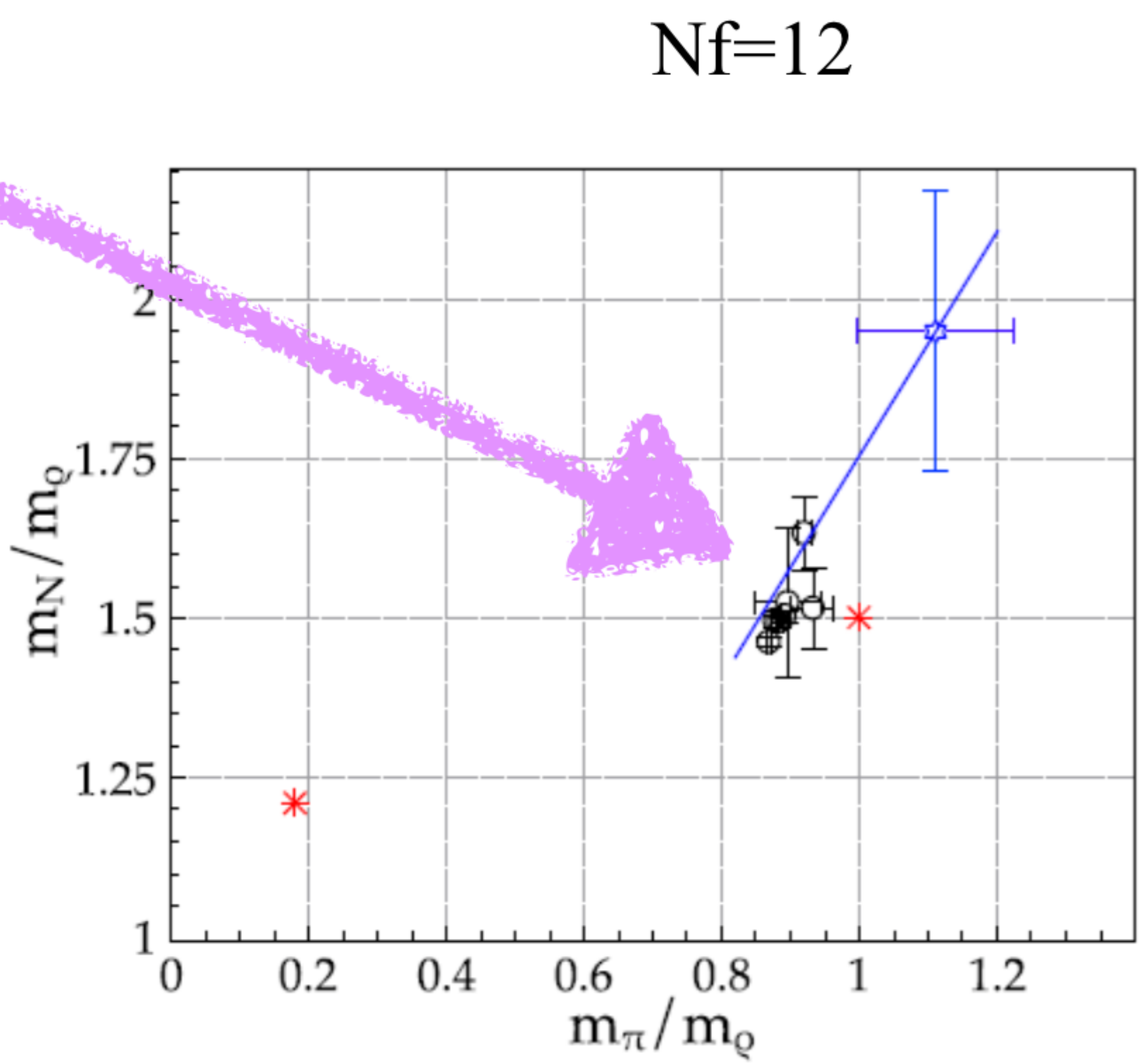
Degeneracy of the chiral partners towards the chiral limit





Ratios in the conformal window at a glance: the Edinburgh plot

Exact conformality: point like



Data show some deviation from exact conformality

da Silva, Miura, Pallante, MpL

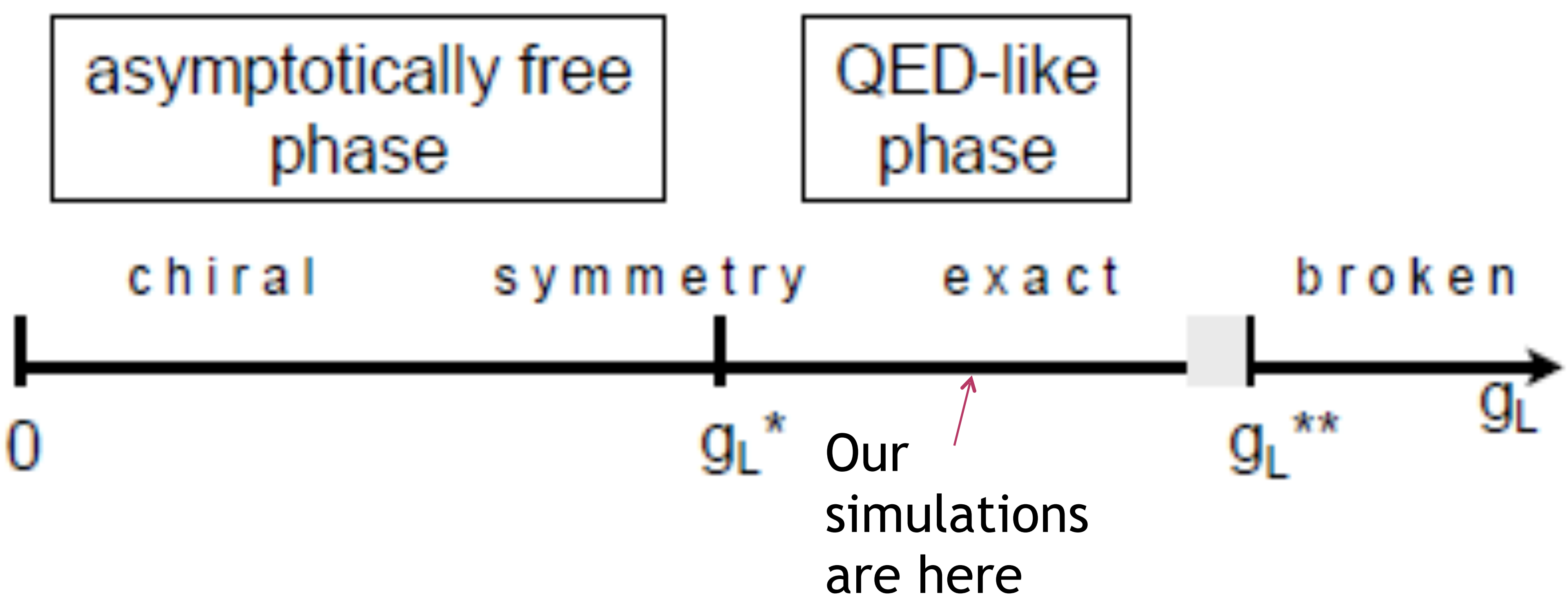
Lattice corrections to conformal scaling

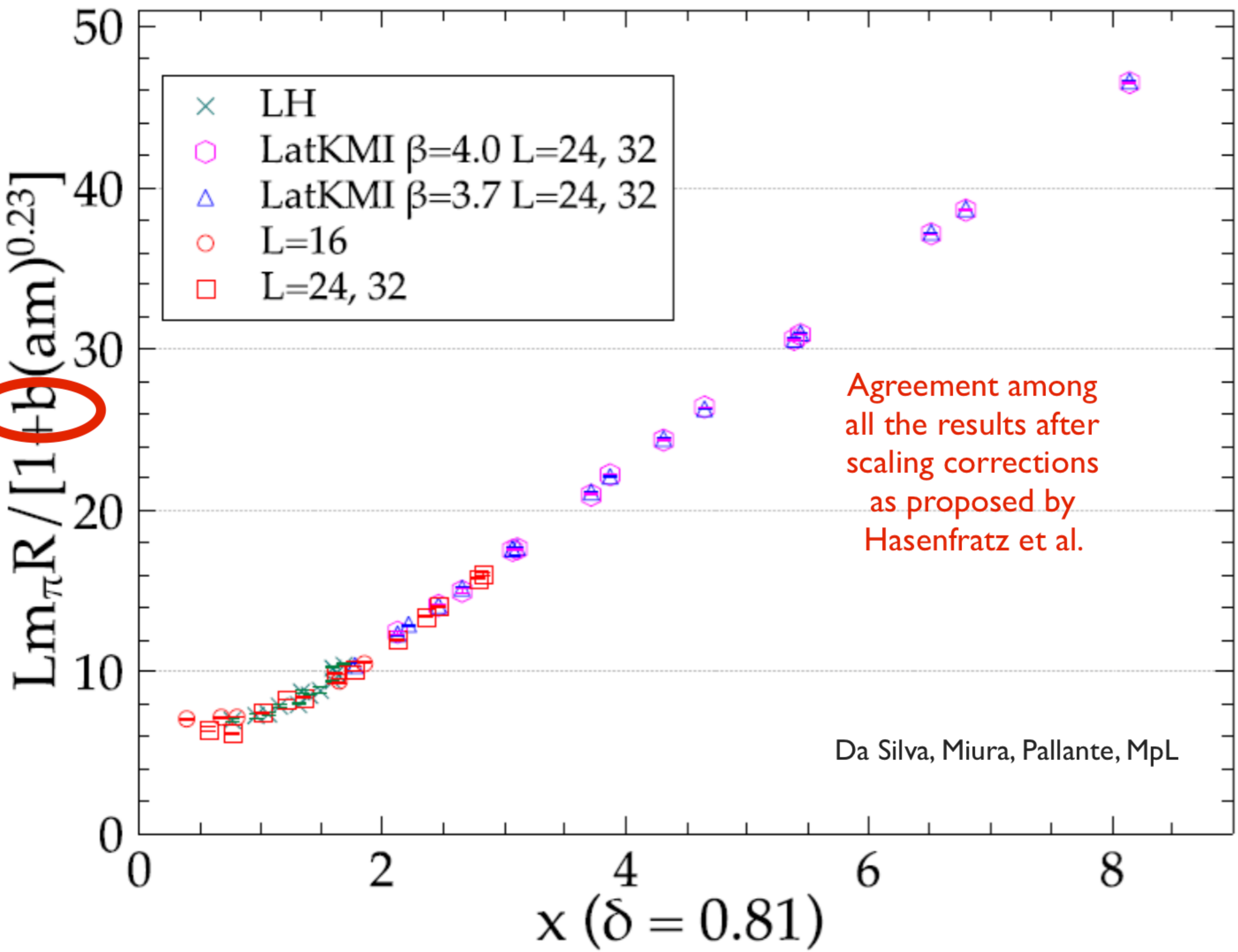
1: Size $$M_H = L^{-1} f_H(x) \qquad x \equiv L m^{1/y_m}$$

2: Coupling $$M_H = L^{-1} f_H\left(x, g_0 m^{\omega}\right)$$

Del Debbio, Zwicky;
Hasenfratz et al;
MpL, da Silva, Miura, Pallante

$$L M_H = F_H(x)\left\{1 + g_0 m^{\omega} G_H(x) + \mathcal{O}\left(g_0^2 m^{2\omega}\right)\right\}$$





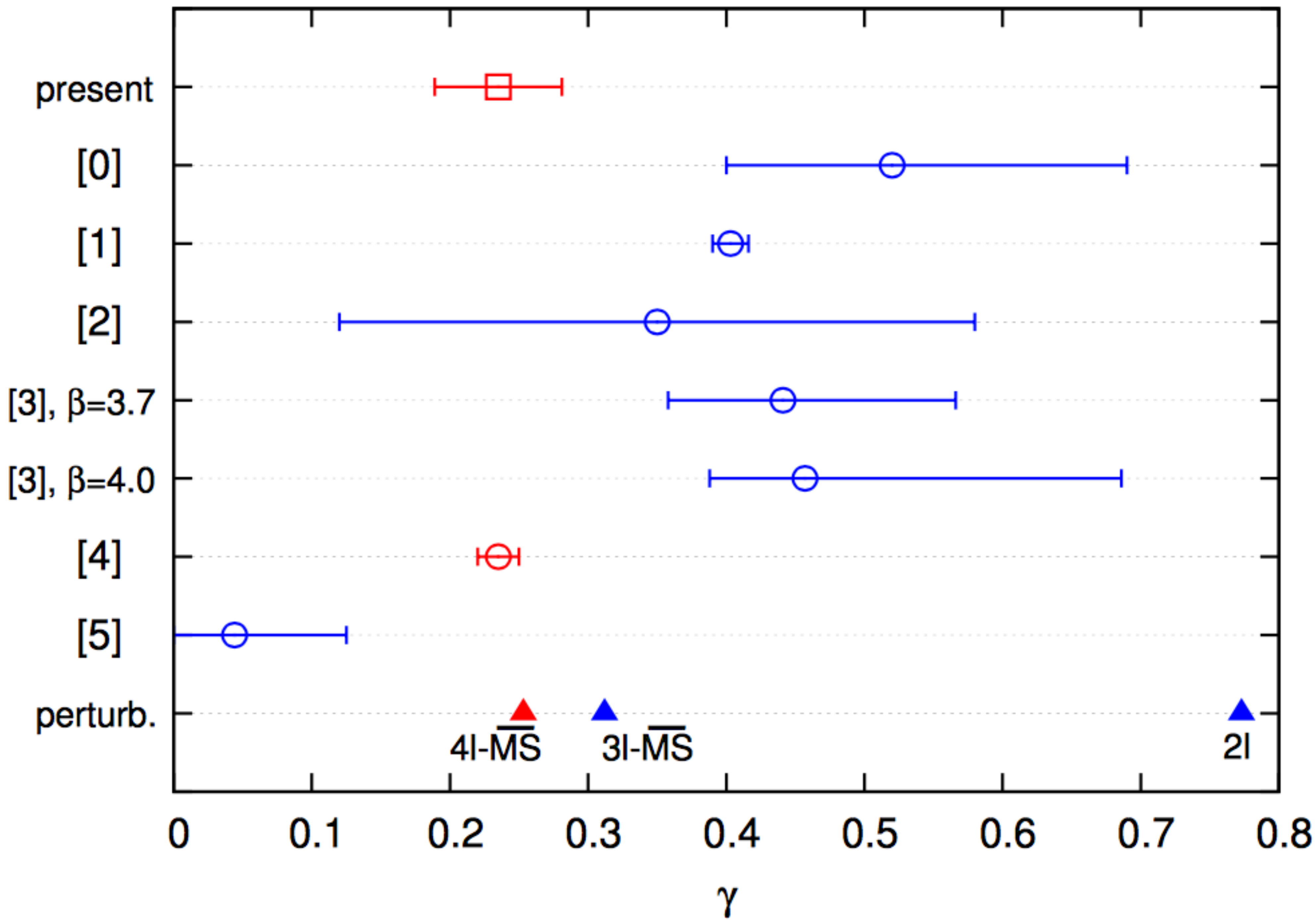
Agreement among all the results after scaling corrections as proposed by Hasenfratz et al.

Da Silva, Miura, Pallante, MpL

Compilation of results for the anomalous dimension, Nf=12

Blue: raw
Red: corrected
(scaling violations
taken into account)

[0] DPL, 2009
[1] LSD coll. 2011
[2] De Grand et al.2011
[3] KMI coll. 2012
[4] Cheng et al. 2014
[5] Itou 2013



MpL, Miura, Nunes da Silva, Pallante 2014

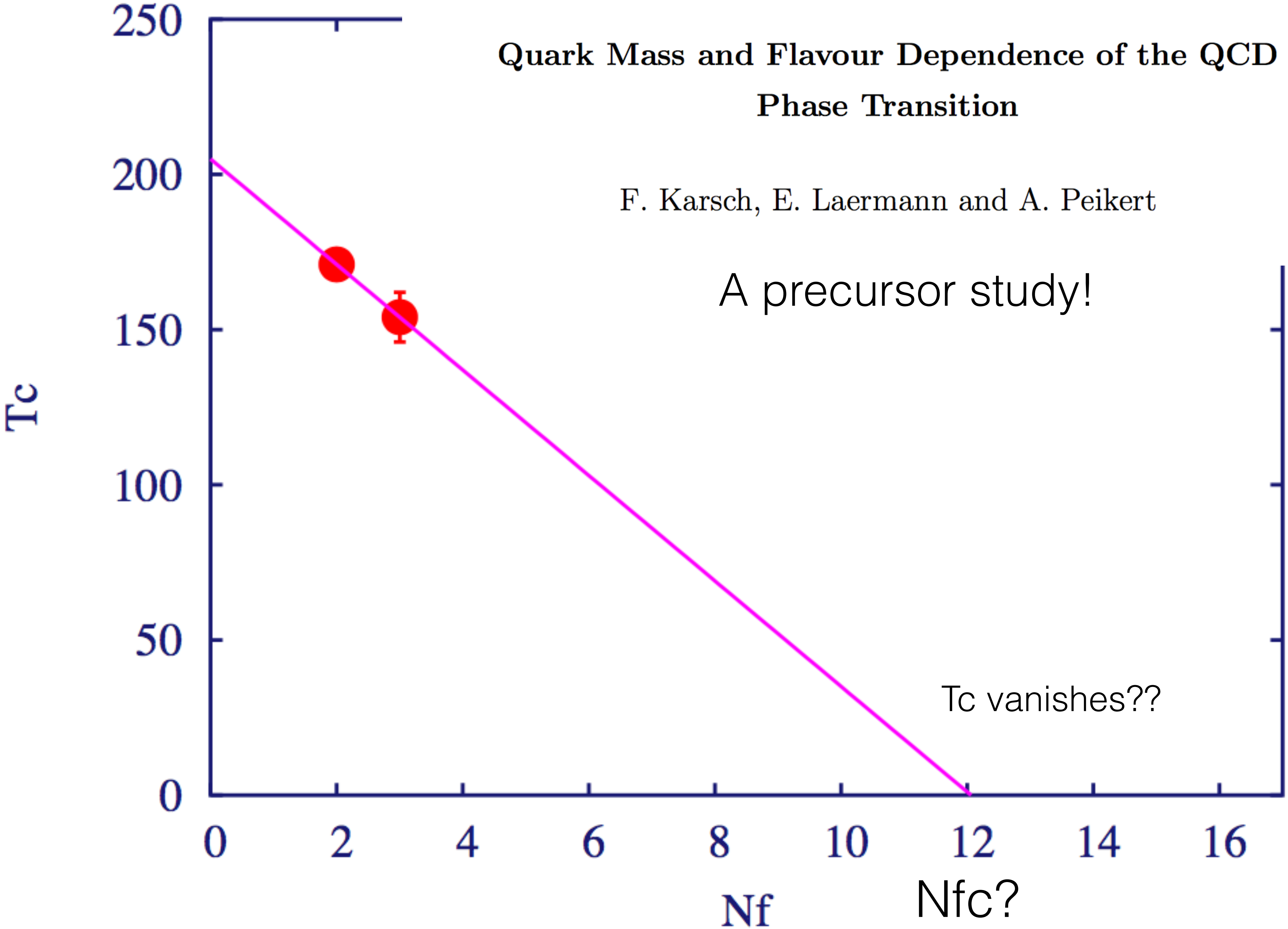

OK
YM
QCD-like
Preconformal
Nfc
Conformal
NAF

II.3 The preconformal window

BI-TP 2000/41

Quark Mass and Flavour Dependence of the QCD Phase Transition

F. Karsch, E. Laermann and A. Peikert



Standard picture of scale separation

$$\Lambda_{IR}/\Lambda_{UV} = \mathcal{O}(1).$$

ΛUV

In the conformal phase IR scales vanish but UV ones survive

$$\frac{\Lambda_{UV}}{\Lambda_{IR}} \sim \exp\left(\frac{\hat{K}}{\sqrt{x_c - x}}\right)$$

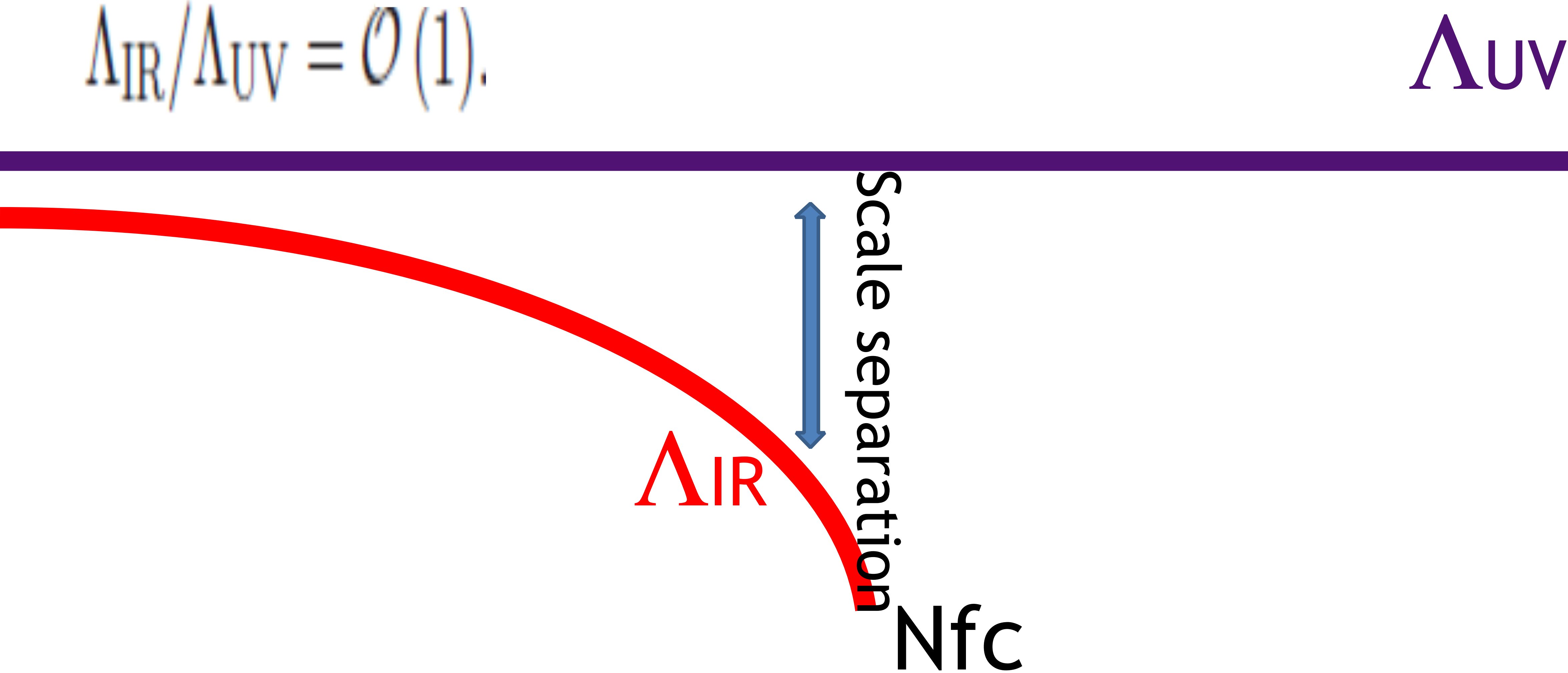
$$x = N_f/N_c$$

The coupling walks for

$$\Lambda_{UV}^{-1} \ll r \ll \Lambda_{IR}^{-1}$$

Standard picture of scale separation

$$\Lambda_{\rm IR}/\Lambda_{\rm UV} = \mathcal{O}(1).$$

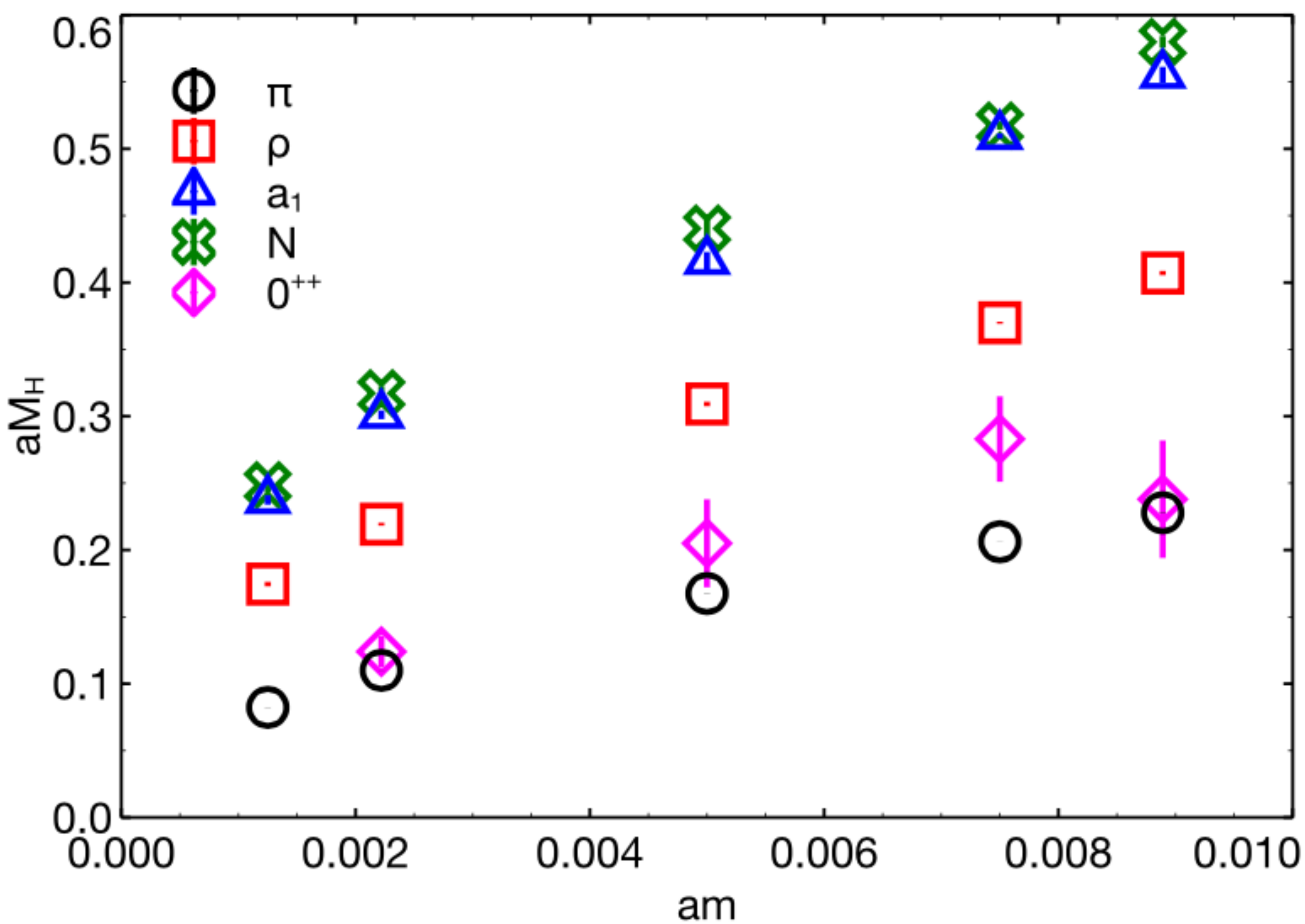


$$\frac{\Lambda_{\rm UV}}{\Lambda_{\rm IR}} \sim \exp\left(\frac{\hat{K}}{\sqrt{x_c - x}}\right)$$

Strongly interacting dynamics and the search for new physics at the LHC

T. Appelquist,[1] R. C. Brower,[2,3] G. T. Fleming,[1,3] A. Hasenfratz,[4,3] X. Y. Jin,[5] J. Kiskis,[6] E. T. Neil,[4,7,3] J. C. Osborn,[5,3] C. Rebbi,[2] E. Rinaldi,[8,3] D. Schaich,[9,3,10] P. Vranas,[8] E. Weinberg,[11] and O. Witzel[12,3]
(Lattice Strong Dynamics (LSD) Collaboration)

Beyond scale separation:

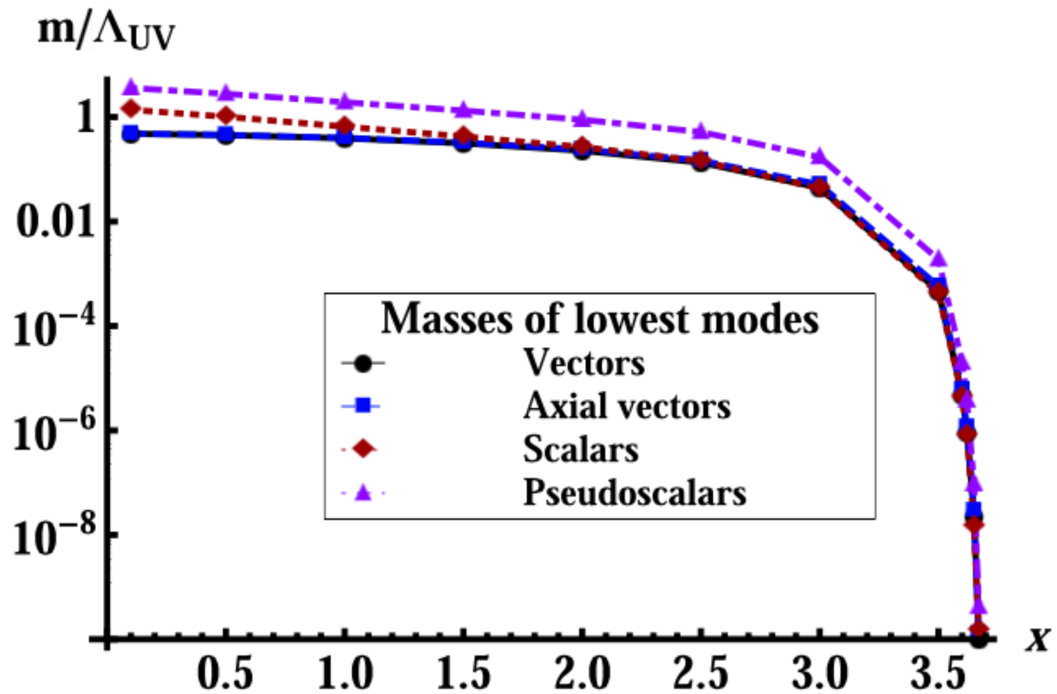


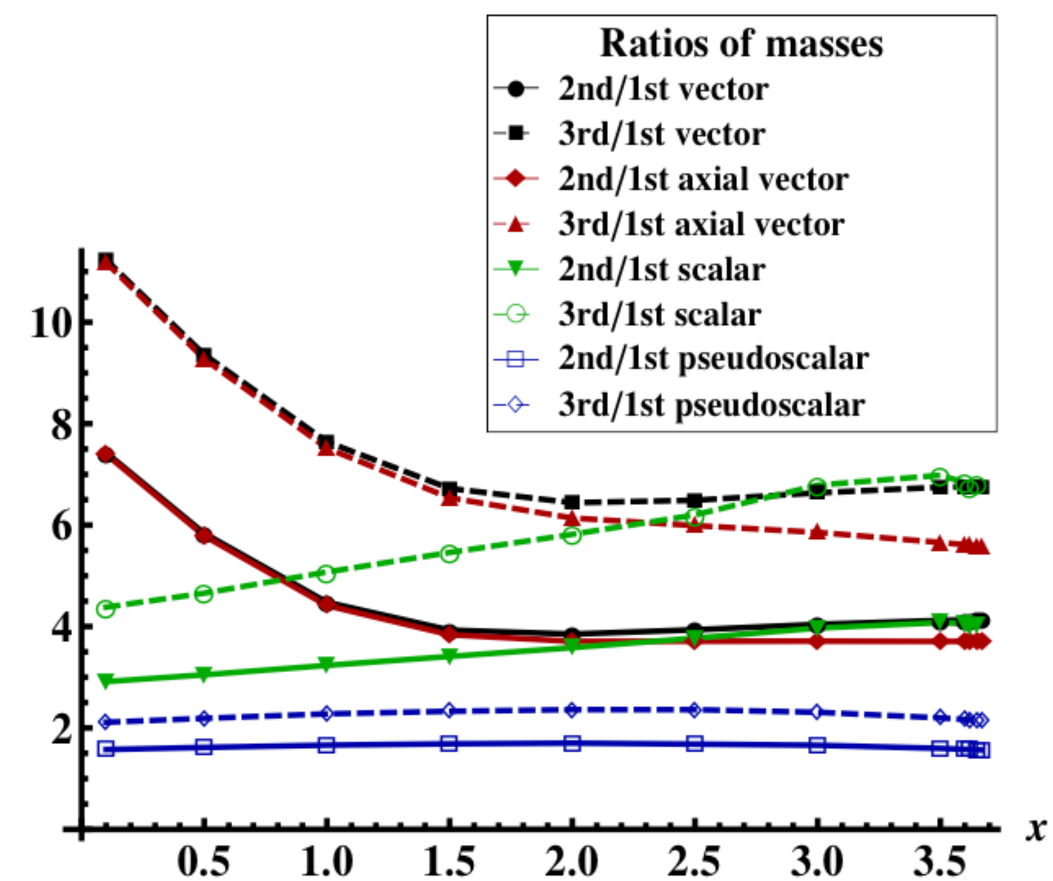
hierarchy of scales in the spectrum: light scalar needed for phenomenology

2016

(Essential) singularity in the chiral limit and mass ratios: example from holographic V-QCD

$$\frac{\Lambda_{\mathrm{UV}}}{\Lambda_{\mathrm{IR}}} \sim \exp\left(\frac{\hat{K}(n+1)}{\sqrt{x_c - x}}\right)$$



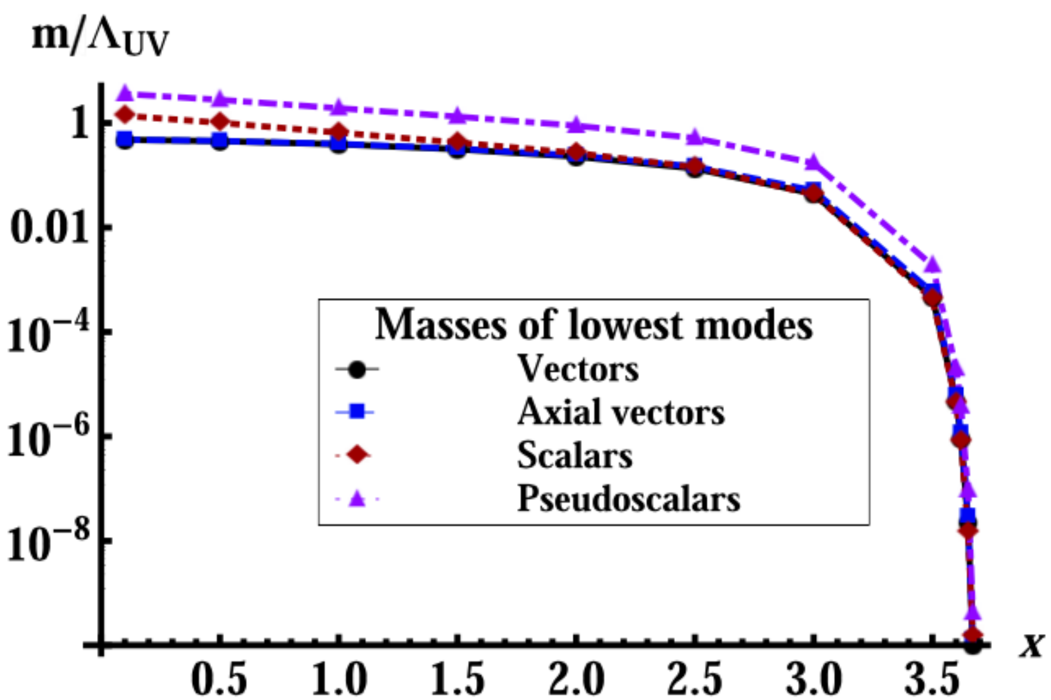


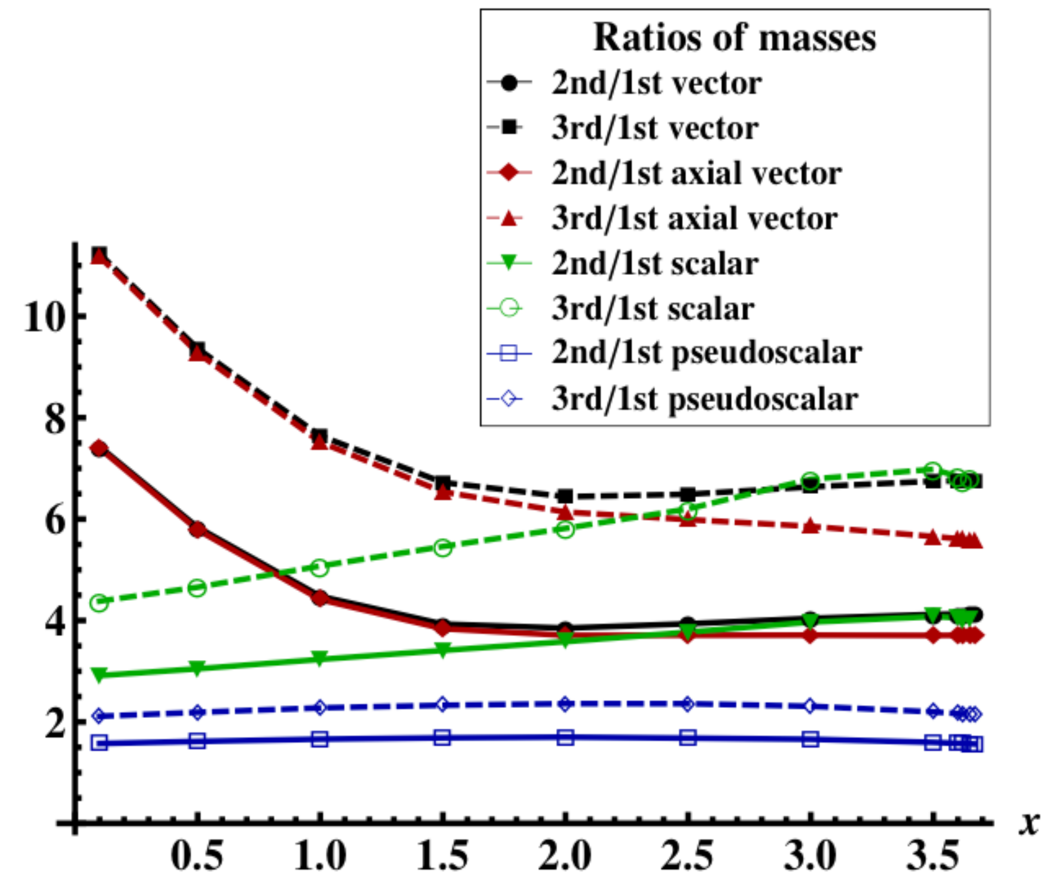
Arean, Iatrakis, Jarvinen, Kiritsis 2013

(Essential) singularity in the chiral limit and mass ratios: example from holographic V-QCD

$$\frac{\Lambda_{\rm UV}}{\Lambda_{\rm IR}} \sim \exp\left(\frac{\hat{K}(n+1)}{\sqrt{x_c - x}}\right)$$

Not unique





Arean, Iatrakis, Jarvinen, Kiritsis 2013

$\overline{\Lambda_{\rm IR}}$ not unique:

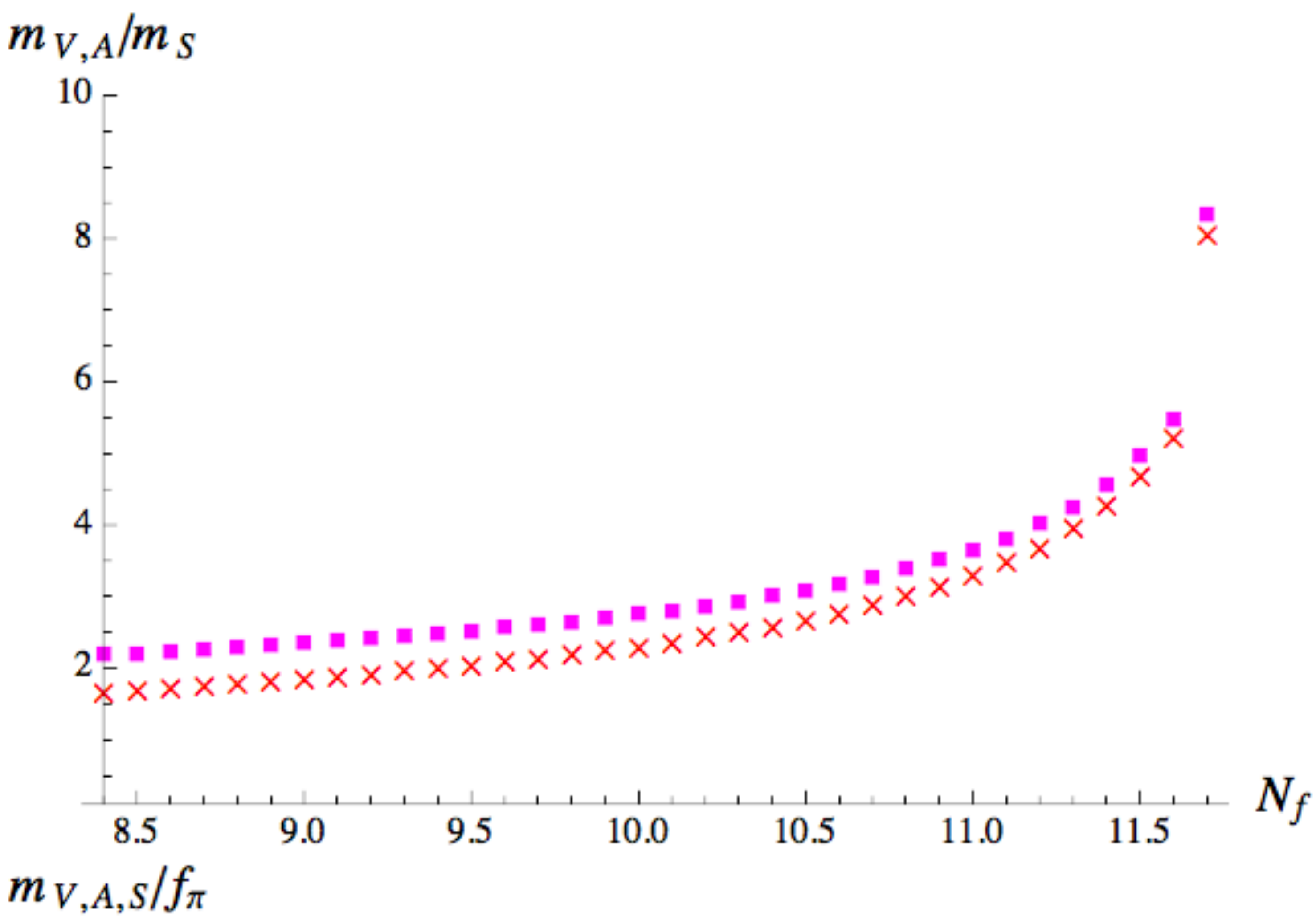
Power-law corrections to essential singularity

Gies et al. 2013
Alho, Evans, Tuominen 2013

$$O_i = A_i (N_f^c - N_f)^{p_i} \langle \bar{q} q \rangle^{1/3}$$

Power-law X Miranski scaling

May account for <u>hierarchy</u> of scales



Mass deformed theory I: EoS approach for IR quantities

$$y = f(x)$$
$$y = m/ < \bar{\psi}\psi >^{\delta} \qquad \delta = \tfrac{6-\eta}{2-\eta}$$

Second order transition:

$$x = ({N_f}^c - N_f)/ < \bar{\psi}\psi >^{\frac{1}{\beta}} \qquad < \bar{\psi}\psi > = ({N_f}^c - N_f)^{\beta}$$

Essential singularity: Nogawa, Hasegawa, Nemoto, 2012

$$x = e^{\sqrt{({N_f}^c - N_f)}}/ < \bar{\psi}\psi > \qquad < \bar{\psi}\psi > = e^{\sqrt{({N_f}^c - N_f)}}$$

Continuity of $f(x)$ plus asymptotic forms for $m \to 0$ and $N_f \to {N_f}^c$ imply

$< \bar{\psi}\psi > \propto e^{\sqrt{({N_f}^c - N_f)}}$ for m *smallish* and $({N_f}^c - N_f)$ *largish*

$< \bar{\psi}\psi > \propto m^{1/\delta}$ for m *largish* and $({N_f}^c - N_f)$ *smallish*

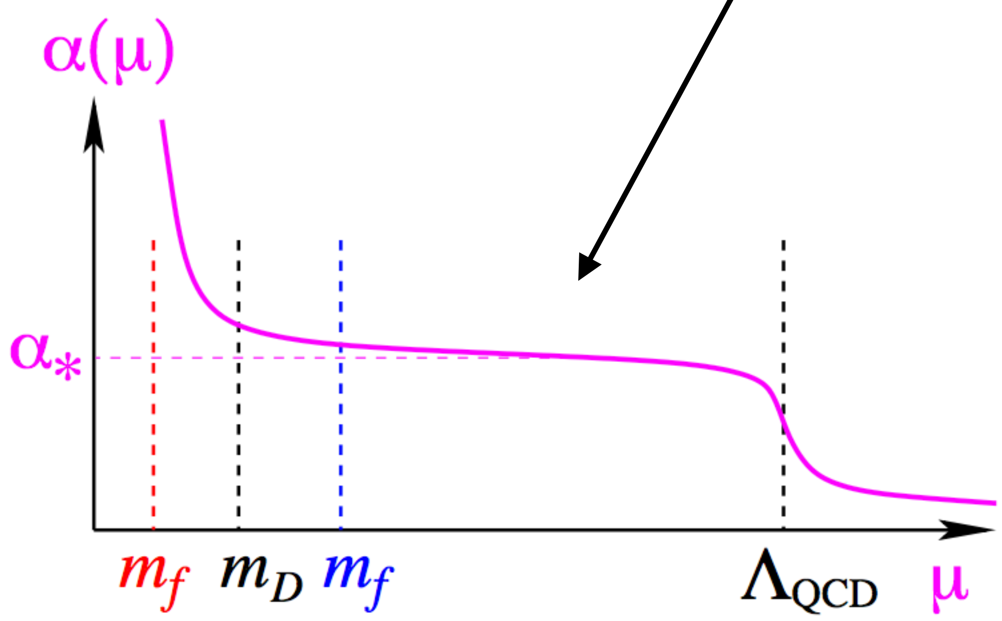
Anomalous dimension appears naturally below Nfc

Scaling limited by Goldstone singularities in the chiral limit (Wallace Zia

Mass deformed theory II: KMI discussion

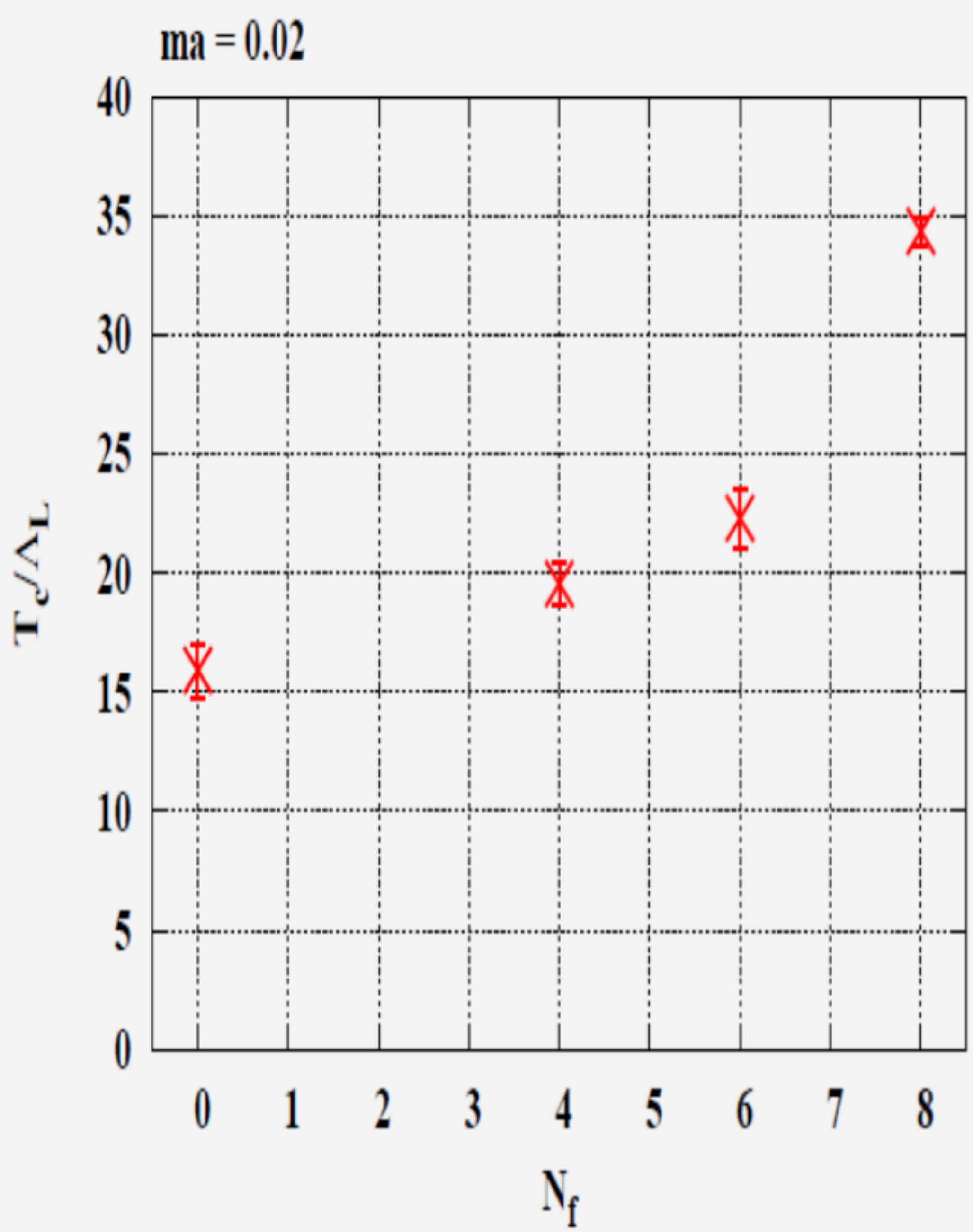
Mutatis mutandis,
Eos approach reproduces KMI scenario:

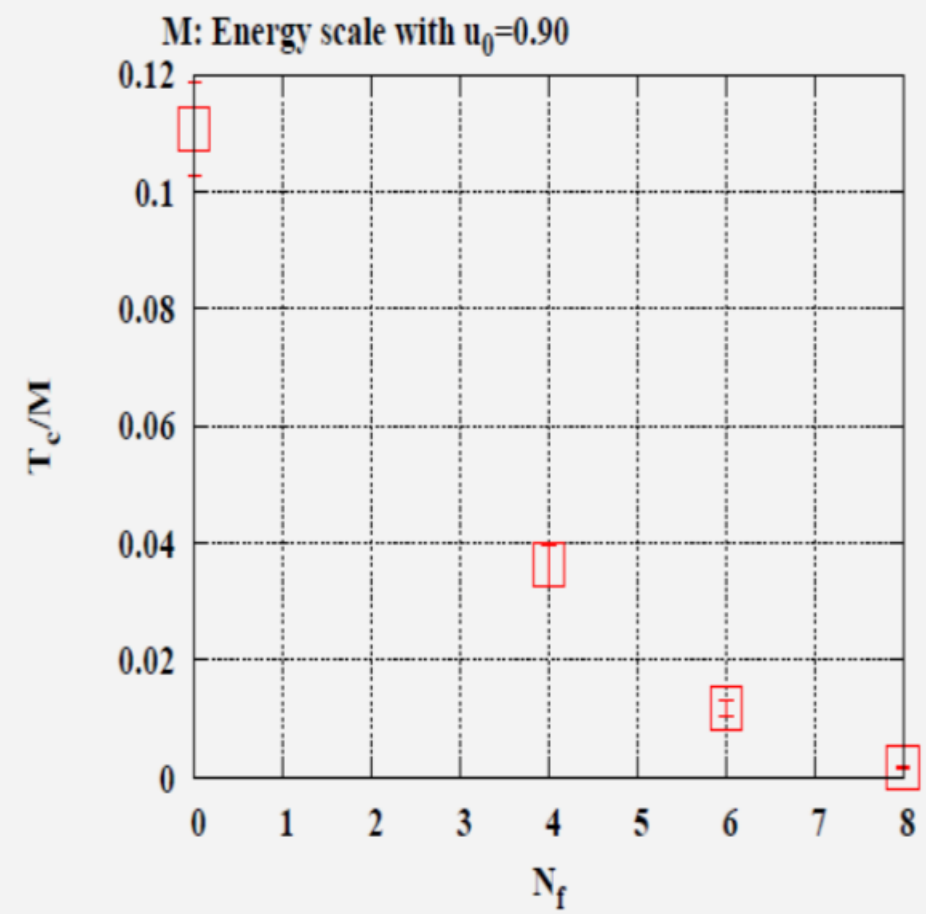
Scaling with anomalous dimension



KMI 2013

Search for scale hierarchy - Kohtaroh Miura, MpL, Tiago Nunes da Silva, E Pallante





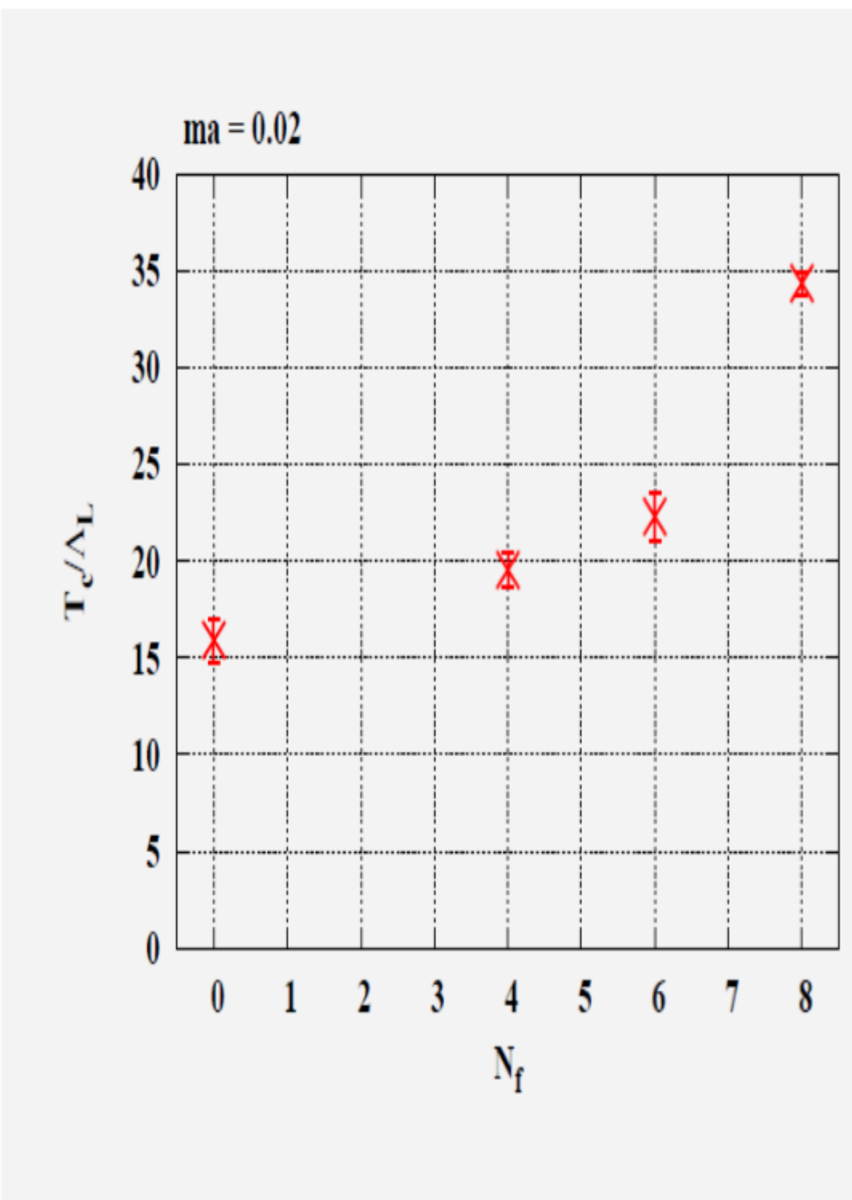
$$\frac{T_c}{M} = \frac{1}{N_t} \exp\left[\int_{g_{\rm ref}}^{g_c} \frac{dg}{B(g)}\right] .$$

K. Miura, MpL, E. Pallante 2012

Towards a quantitive comparison with holography

K. Miura, MpL, E. Pallante, in progress

$$\frac{2\pi T_c}{M_{KK}} = 1 - \frac{1}{126\pi^3}\lambda_4^2\frac{N_f}{N_c}\left(1 + \frac{12\pi^{3/2}}{\Gamma\left(-\frac{2}{3}\right)\Gamma\left(\frac{1}{6}\right)}\right)$$

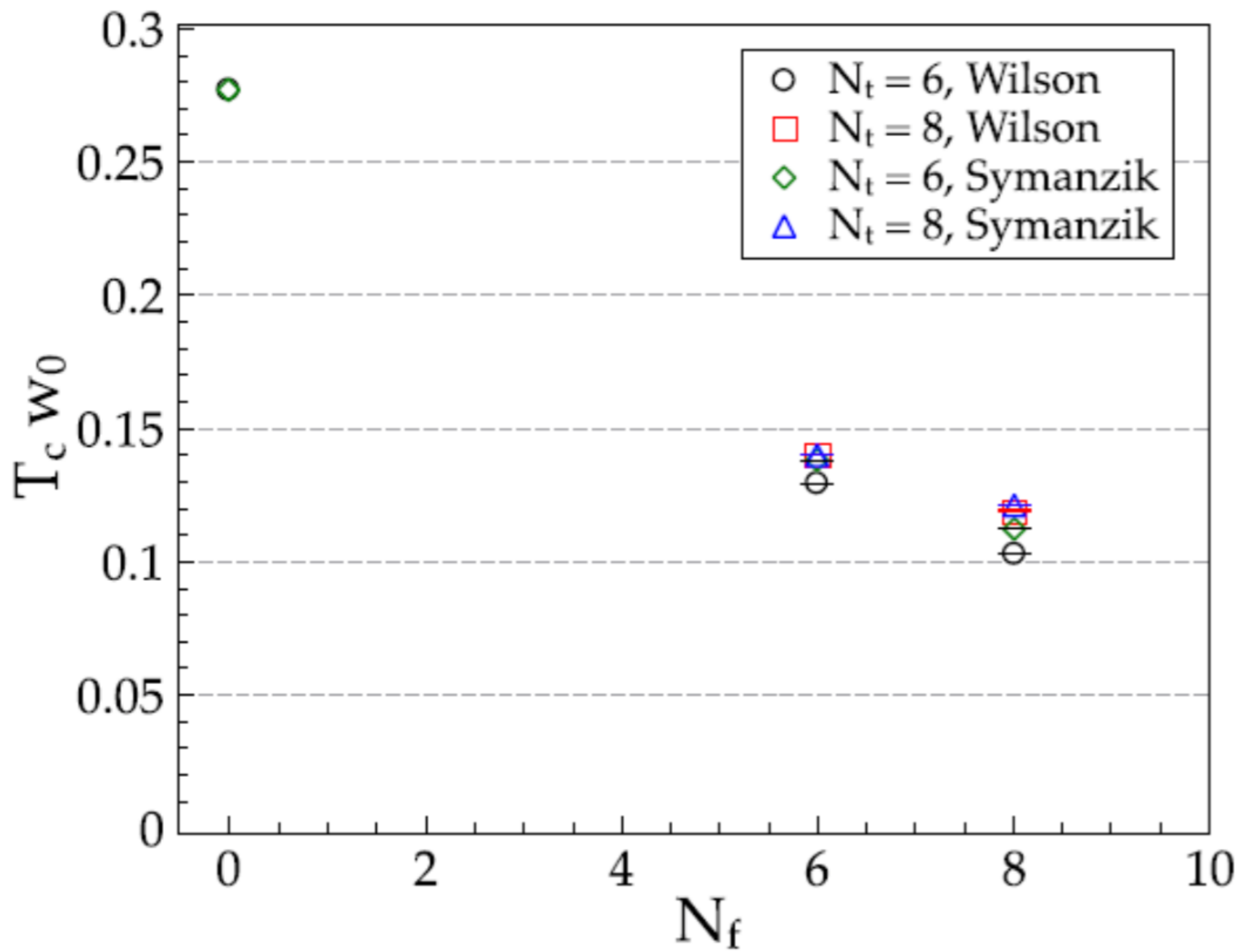


Bigazzi and Cotrone, JHEP 2015

$$\left(1 + \frac{12\pi^{3/2}}{\Gamma\left(-\frac{2}{3}\right)\Gamma\left(\frac{1}{6}\right)}\right) \approx -1.987$$

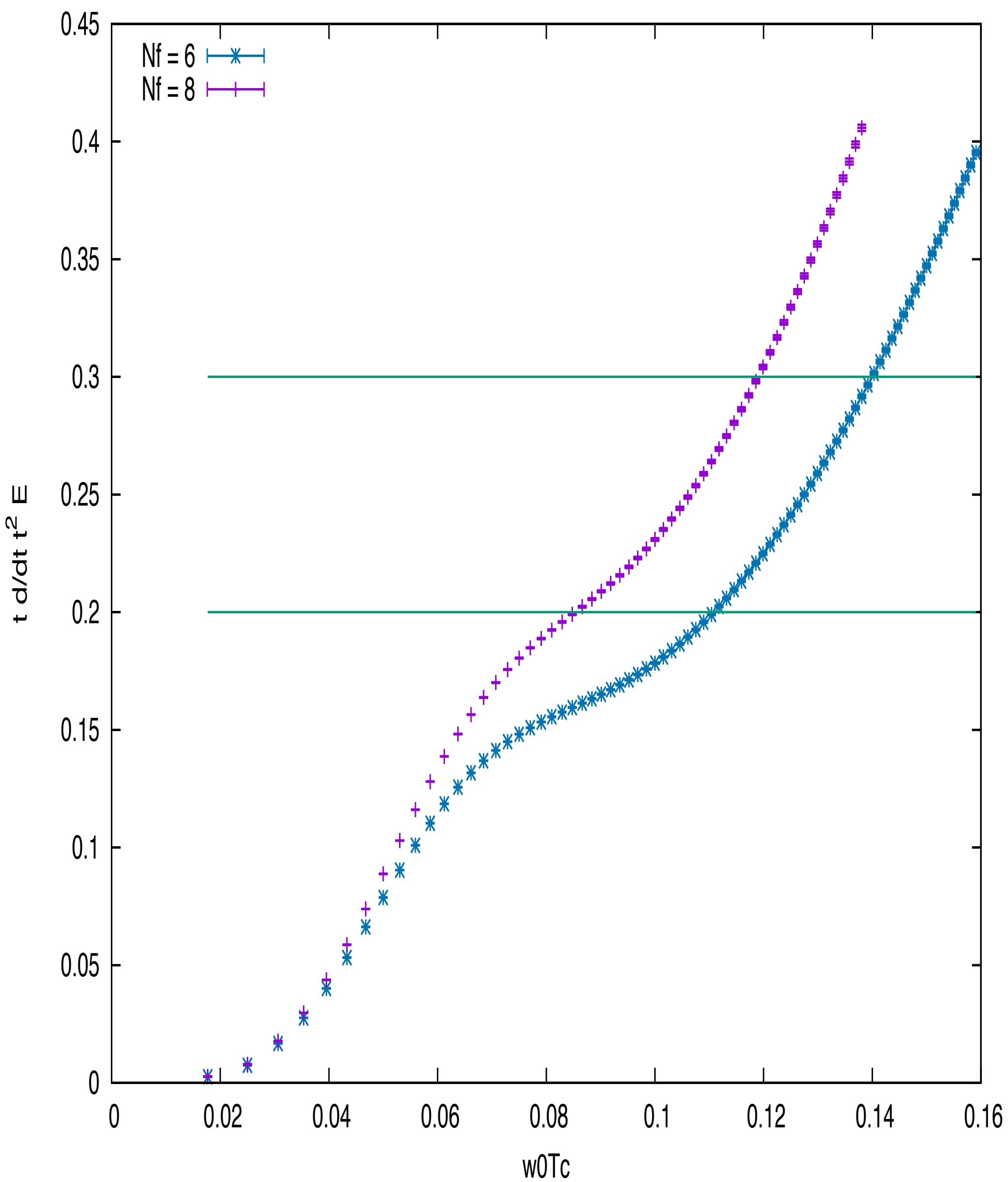
T increases with Nf on the scales
used in these two studies

Tc on the 1/w0 scale

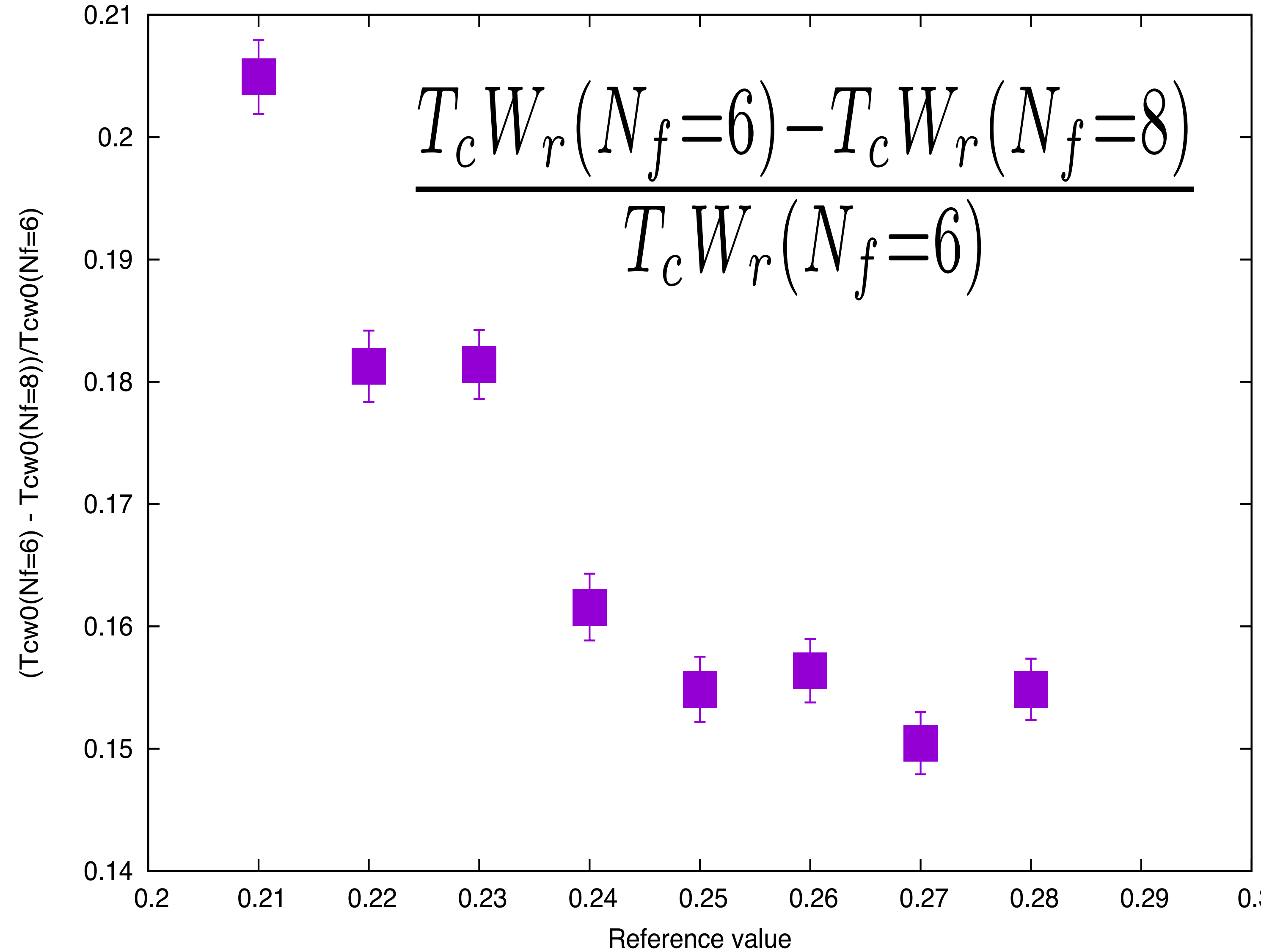


K. Miura, MpL, E.Pallante, in progress

Moving the scale with Wilson flow



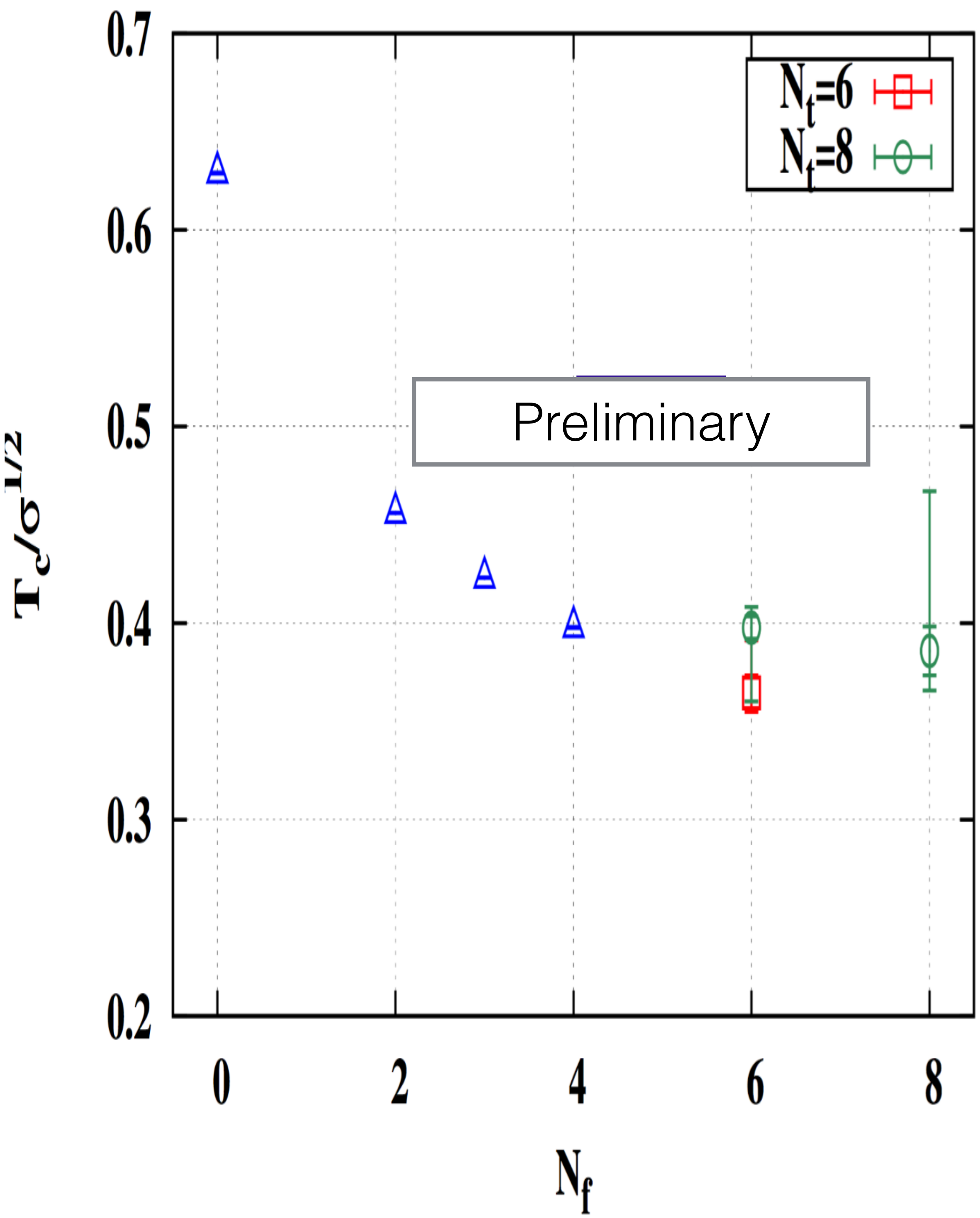
Qualitatively as expected,
limited by lattice artifacts



UV

Tc and the string tension

KM, MpL, EP, in progress



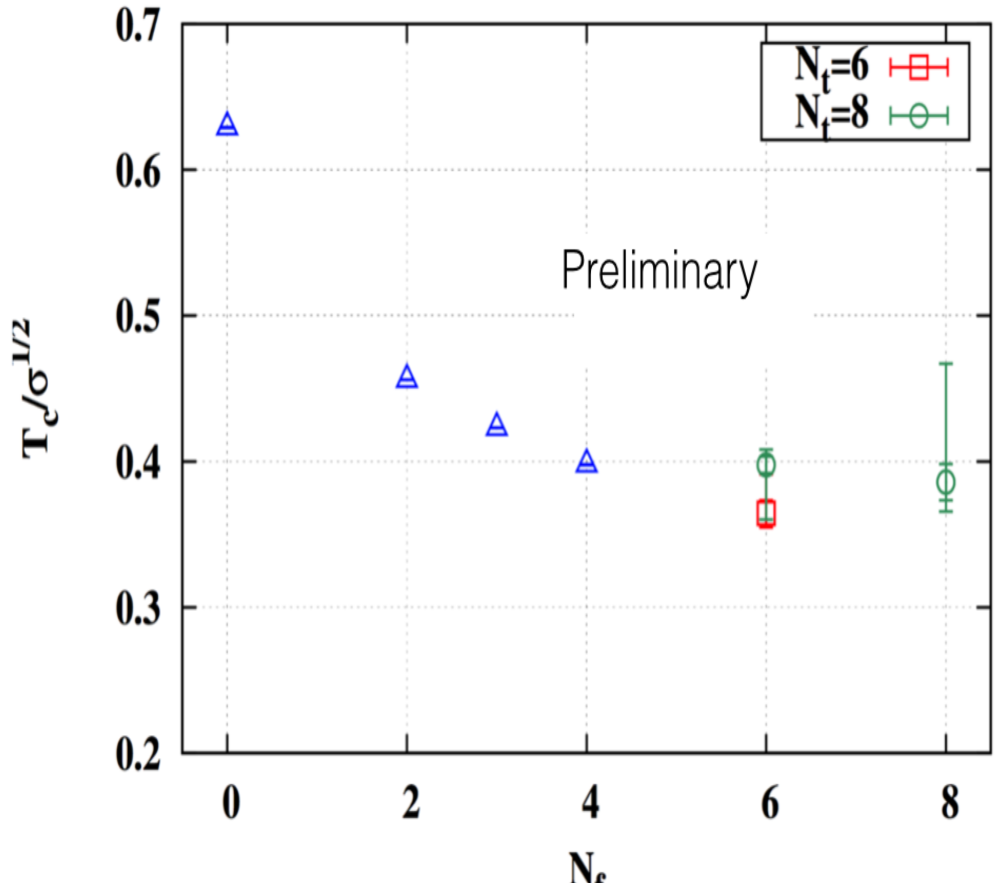
Mild decrease, possibly constant as $N_f \to N_f^c$

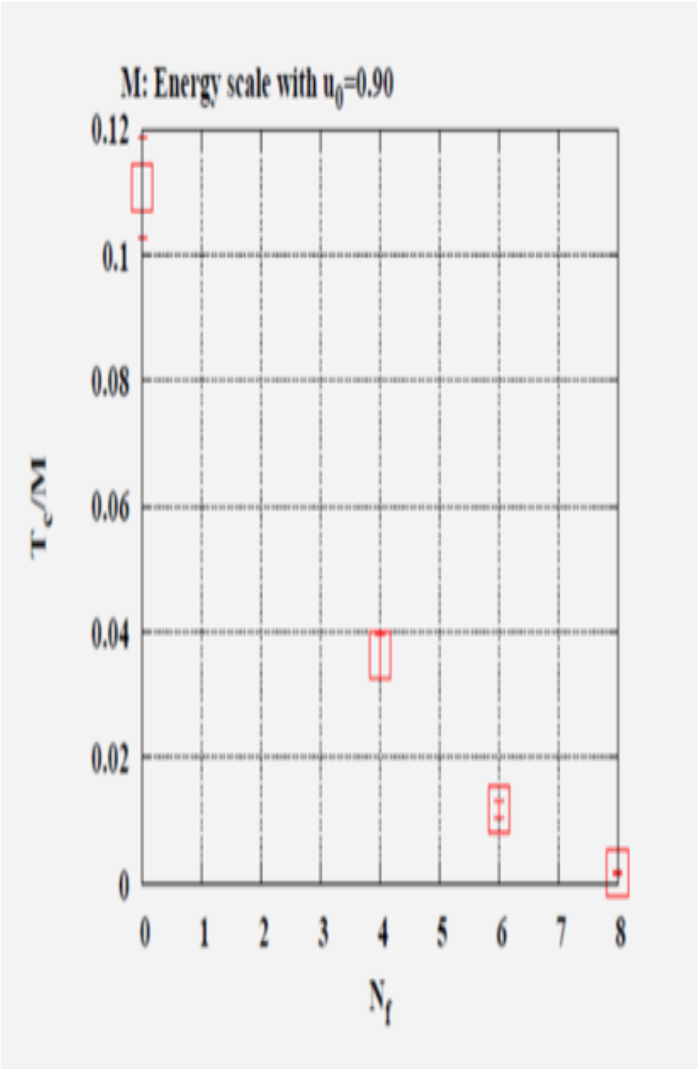
Again similar to the prediction of the WSS model:

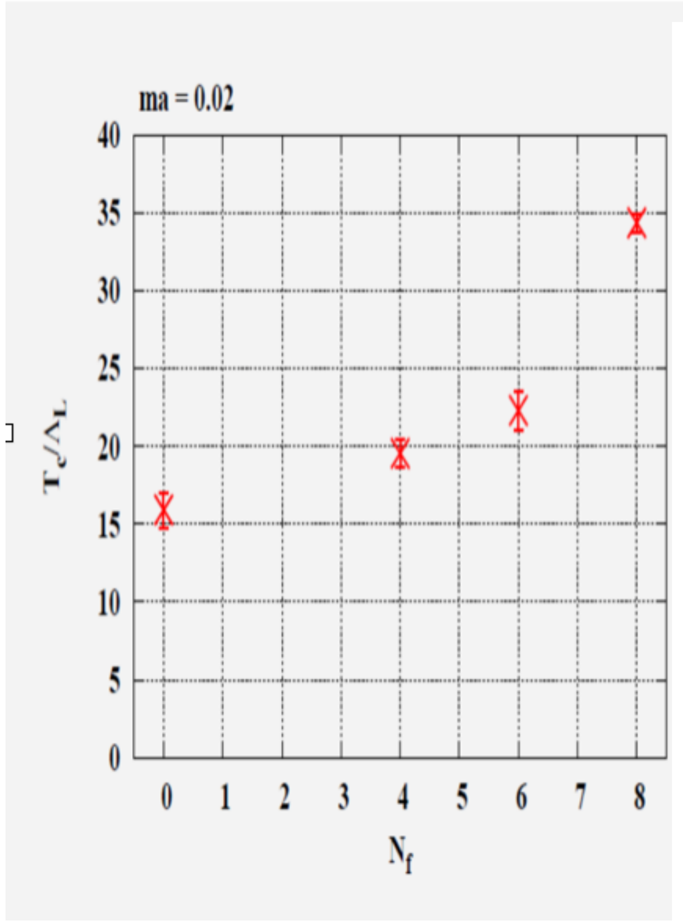
$$\frac{T_c}{\sqrt{\sigma}} \propto (1 - \epsilon N_f/N_c)$$

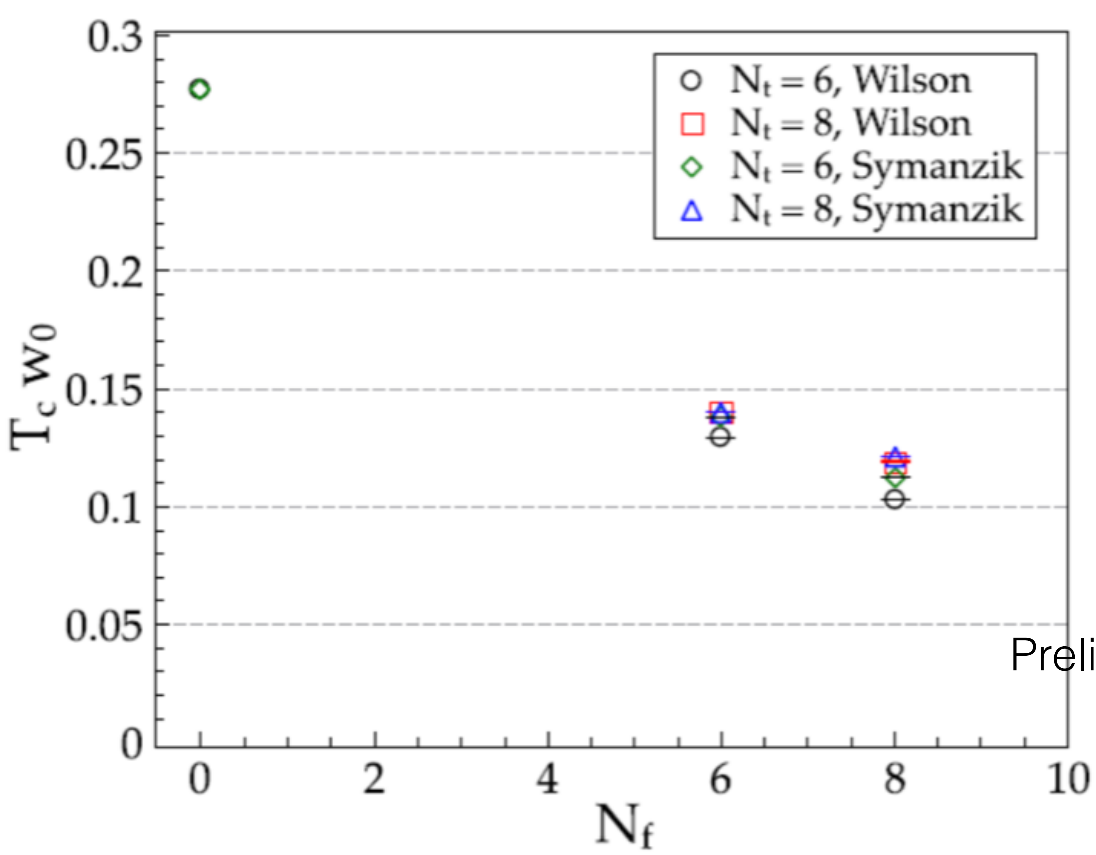
communicated by F. Bigazzi

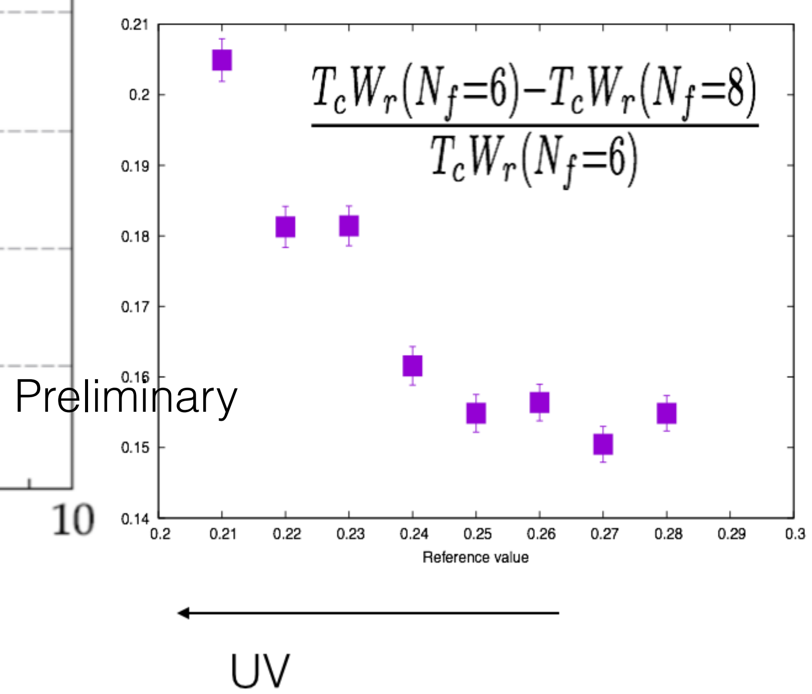
Hierarchy of scales in the near conformal phase



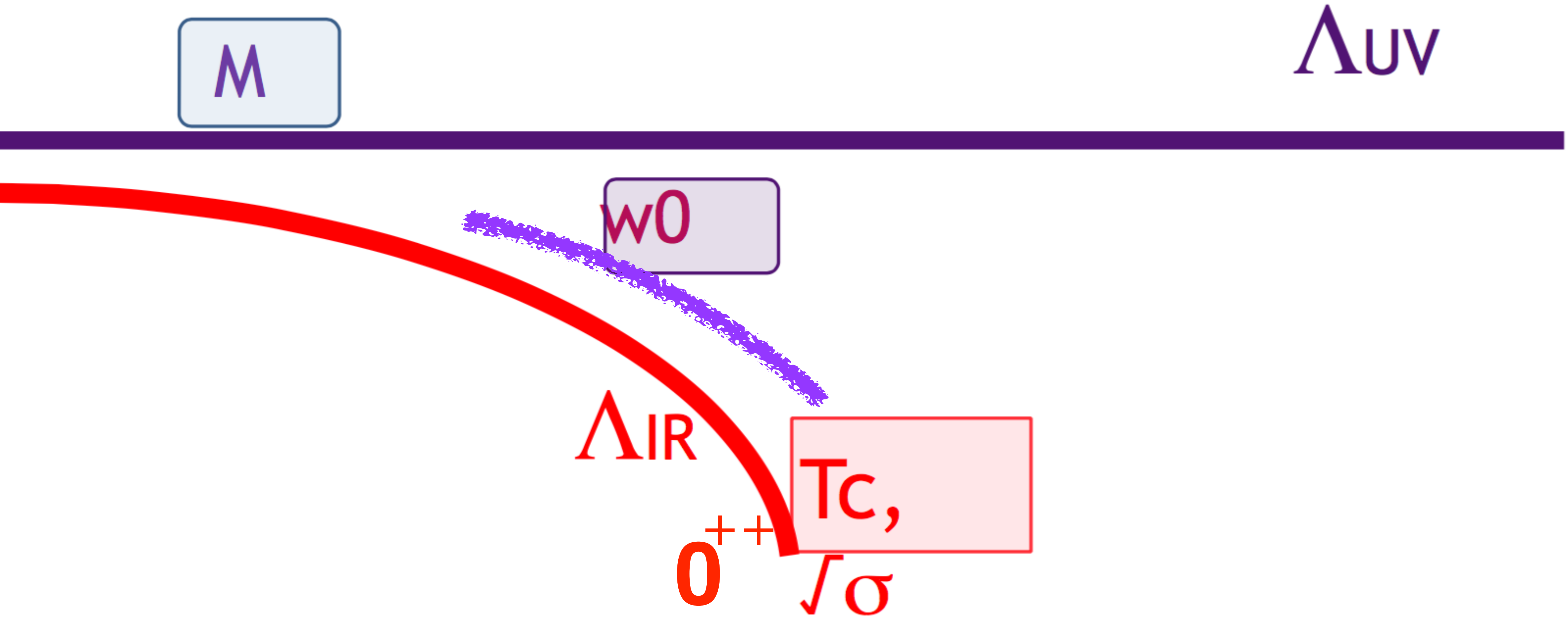








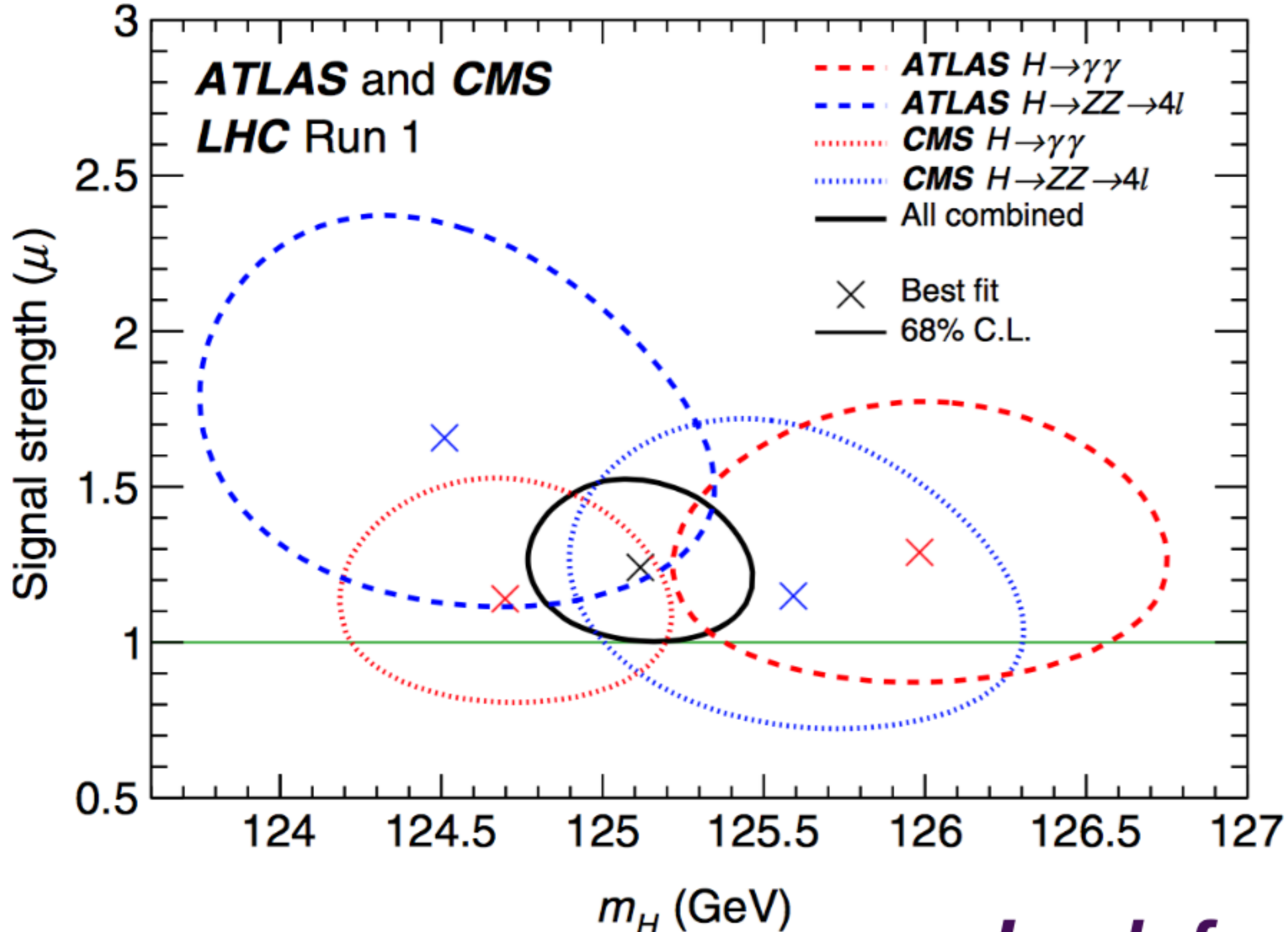
Hierarchy of scales



Short detour on phenomenology

Beyond the Standard Model:

Can we find a theory which produces a narrow Higgs-like status?



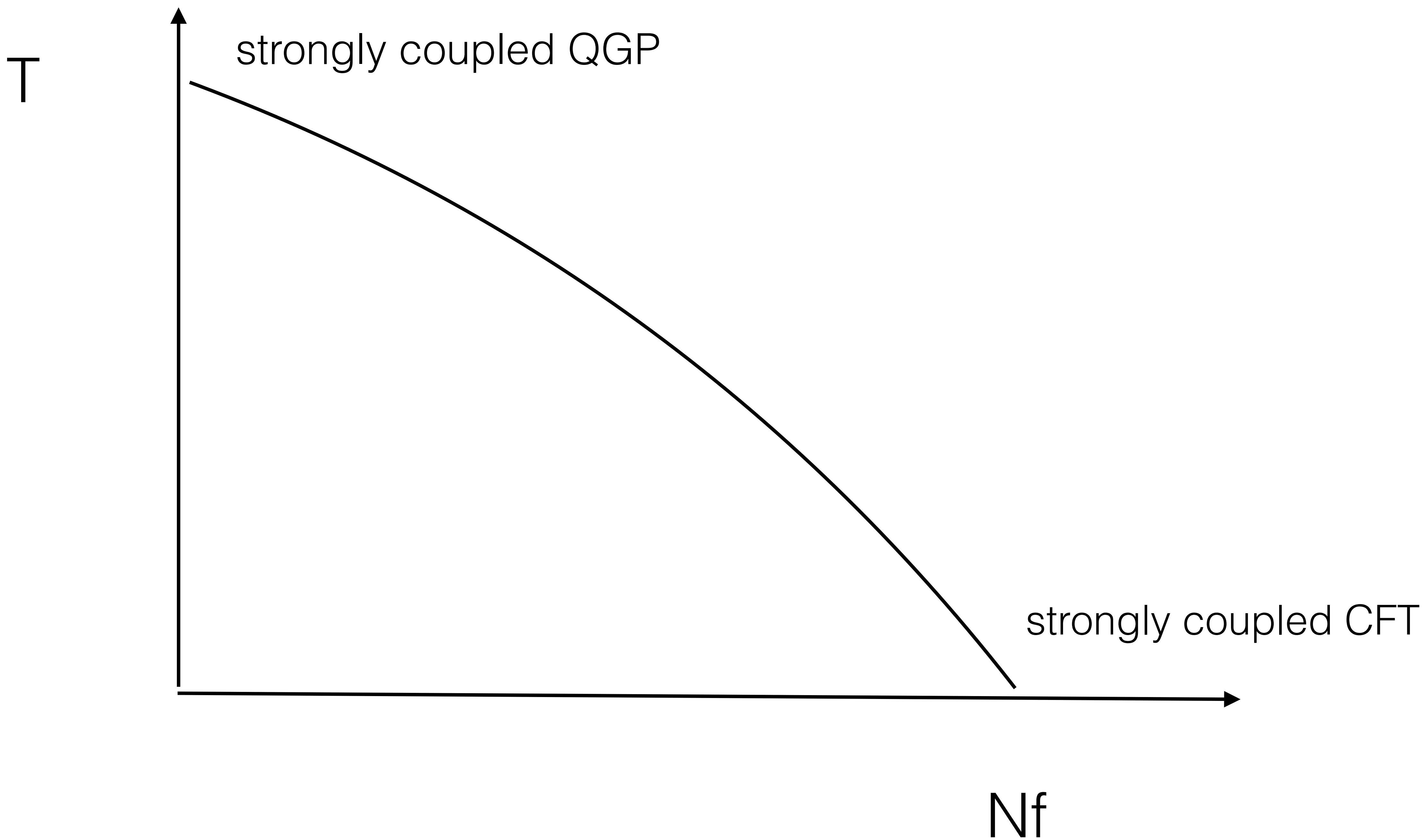
Maybe in the preconformal region?

It should be a composite scalar particle, lighter then so-far unobserved composite vector states

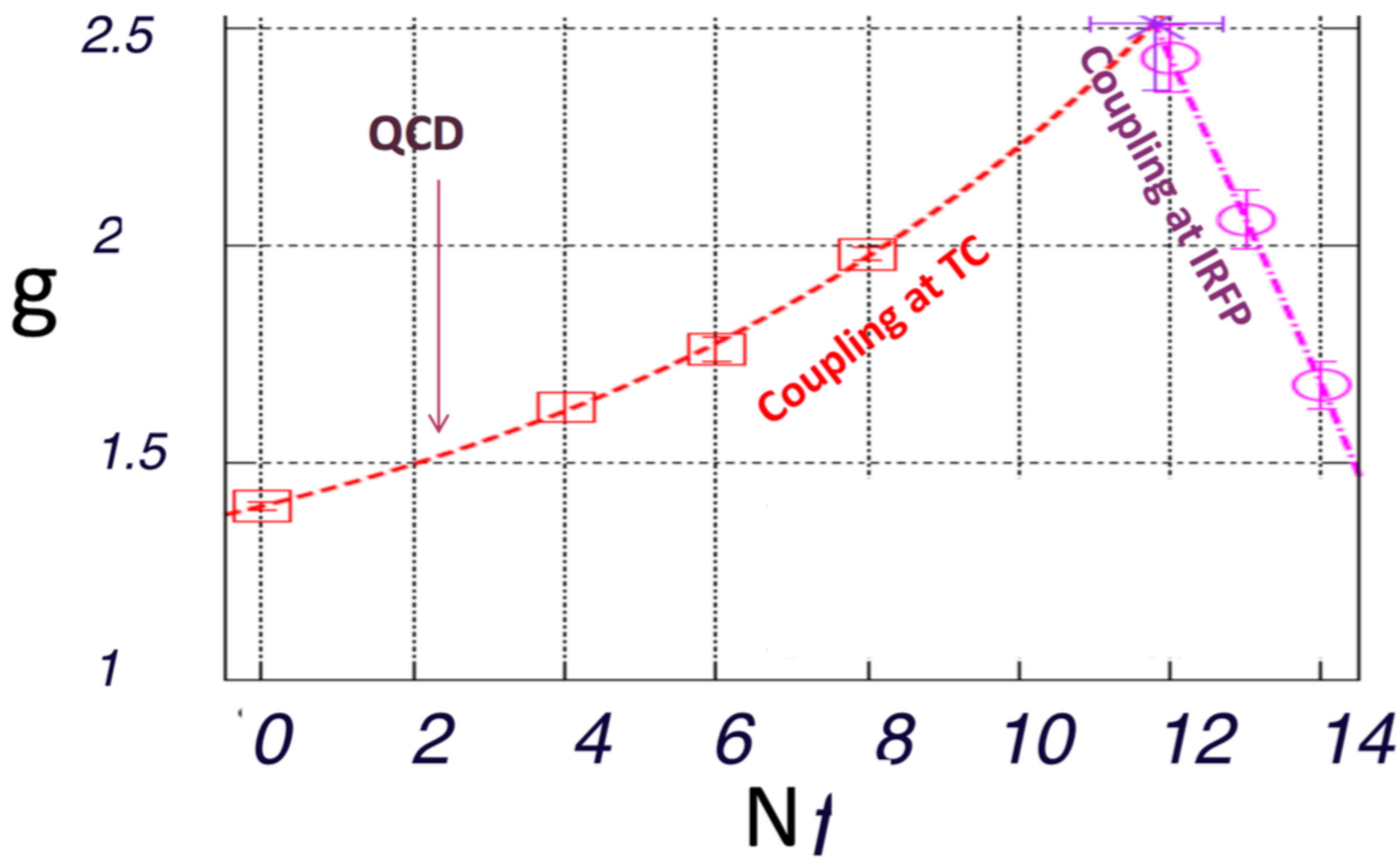
Look for theories with scale separation

..as possible BSM candidates

Parting comments on the phase diagram



sQGP and strongly coupled conformal QCD are continuously connected



The strenght of the coupling increases with Nf

Miura, MpL 2013

Conformality ubiquitous

Approach to the free field

Bulk viscosity set to zero

AdS/CFT methods

Speed of sound close to 0.3

Coupling slowly running :

Hints of conformality also at Strong coupling