Higgs physics near the conformal window

Lattice Higgs Collaboration (L$_{at}$HC)

Zoltan Fodor, Kieran Holland, Santanu Mondal,
Daniel Nogradi, Chik Him Wong

Julius Kuti

University of California, San Diego

Lattice 2014 Symposium, July 23-28, 2014

Lattice 2014

**USQCD
ALCC**

Talk is based on 6 publications, with an overview and added discussion of new developments

Szabolcs Borsanyi, Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong.
July 2014, in preparation

The lattice gradient flow at tree-level and its improvement

Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong. Jun 3, 2014. 14 pp.
e-Print: arXiv:1406.0827 [hep-lat]

The chiral condensate from the Dirac spectrum in BSM gauge theories

Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong. Feb 24, 2014. 7 pp.
Conference: C13-07-29.1 Proceedings
e-Print: arXiv:1402.6029 [hep-lat] | PDF

Can a light Higgs impostor hide in composite gauge models?

Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong. Jan 9, 2014. 7 pp.
Conference: C13-07-29.1 Proceedings
e-Print: arXiv:1401.2176 [hep-lat] | PDF

The Yang-Mills gradient flow in finite volume

Zoltan Fodor (Wuppertal U. & IAS, Julich & Eotvos U.), Kieran Holland (U. Pacific, Stockton & Bern U.), Julius Kuti (UC, San Diego), Daniel Nogradi (Eotvos U.), Chik Him Wong (UC, San Diego). Aug 2012. 17 pp.
Published in **JHEP 1211 (2012) 007**
DOI: 10.1007/JHEP11(2012)007
e-Print: arXiv:1208.1051 [hep-lat] | PDF

Can the nearly conformal sextet gauge model hide the Higgs impostor?

Zoltan Fodor (Wuppertal U. & IAS, Julich & Eotvos U.), Kieran Holland (U. Pacific, Stockton), Julius Kuti (UC, San Diego), Daniel Nogradi (Eotvos U.), Chris Schroeder (LLNL, Livermore), Chik Him Wong (UC, San Diego). Sep 2012. 10 pp.
Published in **Phys.Lett. B718 (2012) 657-666**
DOI: 10.1016/j.physletb.2012.10.079
e-Print: arXiv:1209.0391 [hep-lat] | PDF

Outline

Near-conformal light Higgs?

light scalar (dilaton-like?) close to conformal window?
EW precision and S-parameter
scale setting and spectroscopy Wong's talk 2C

Running coupling

running (walking?) coupling from gradient flow
Nogradi 7E Thursday
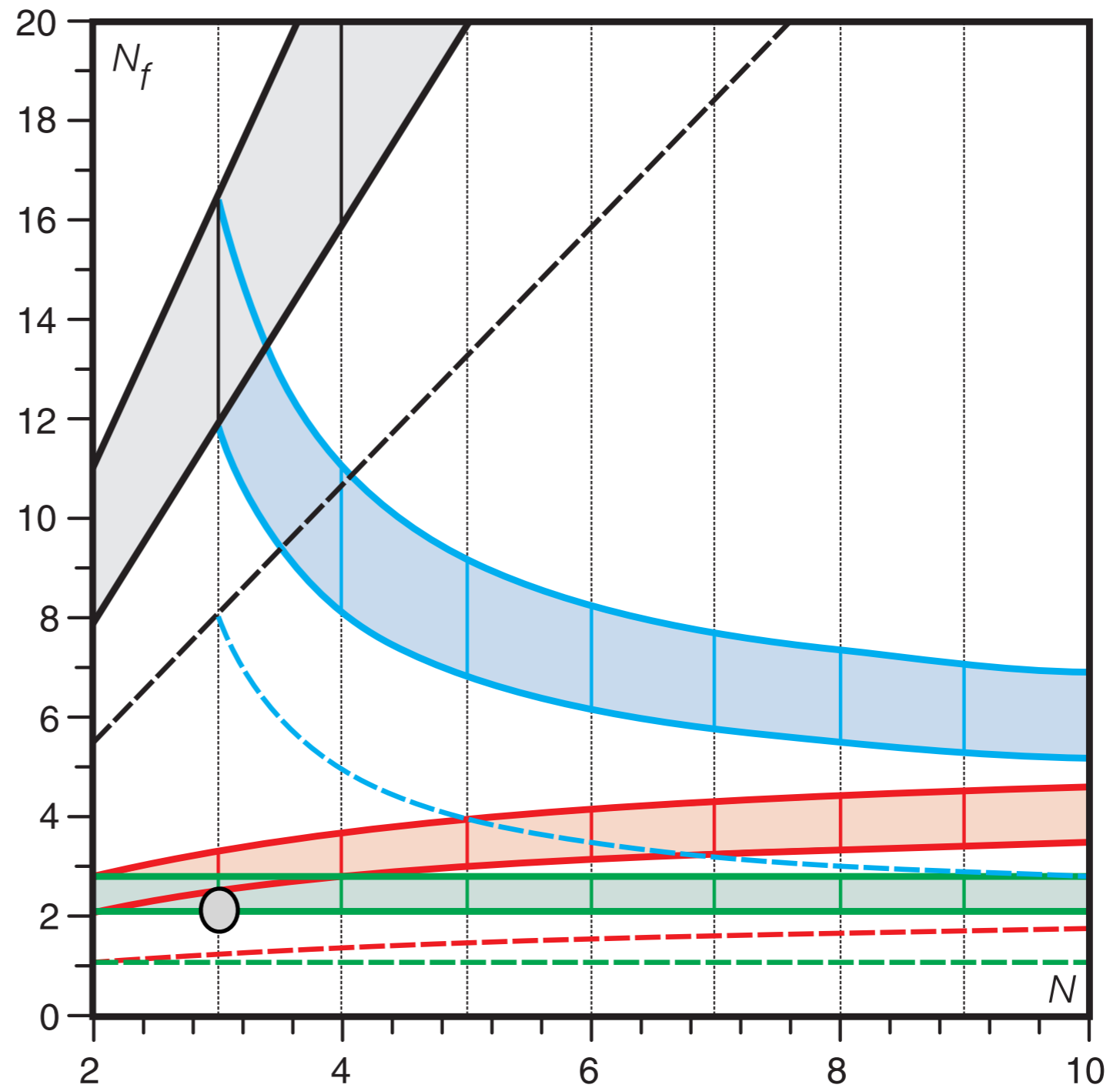
Chiral condensate

new stochastic method for spectral density
mode number
topology
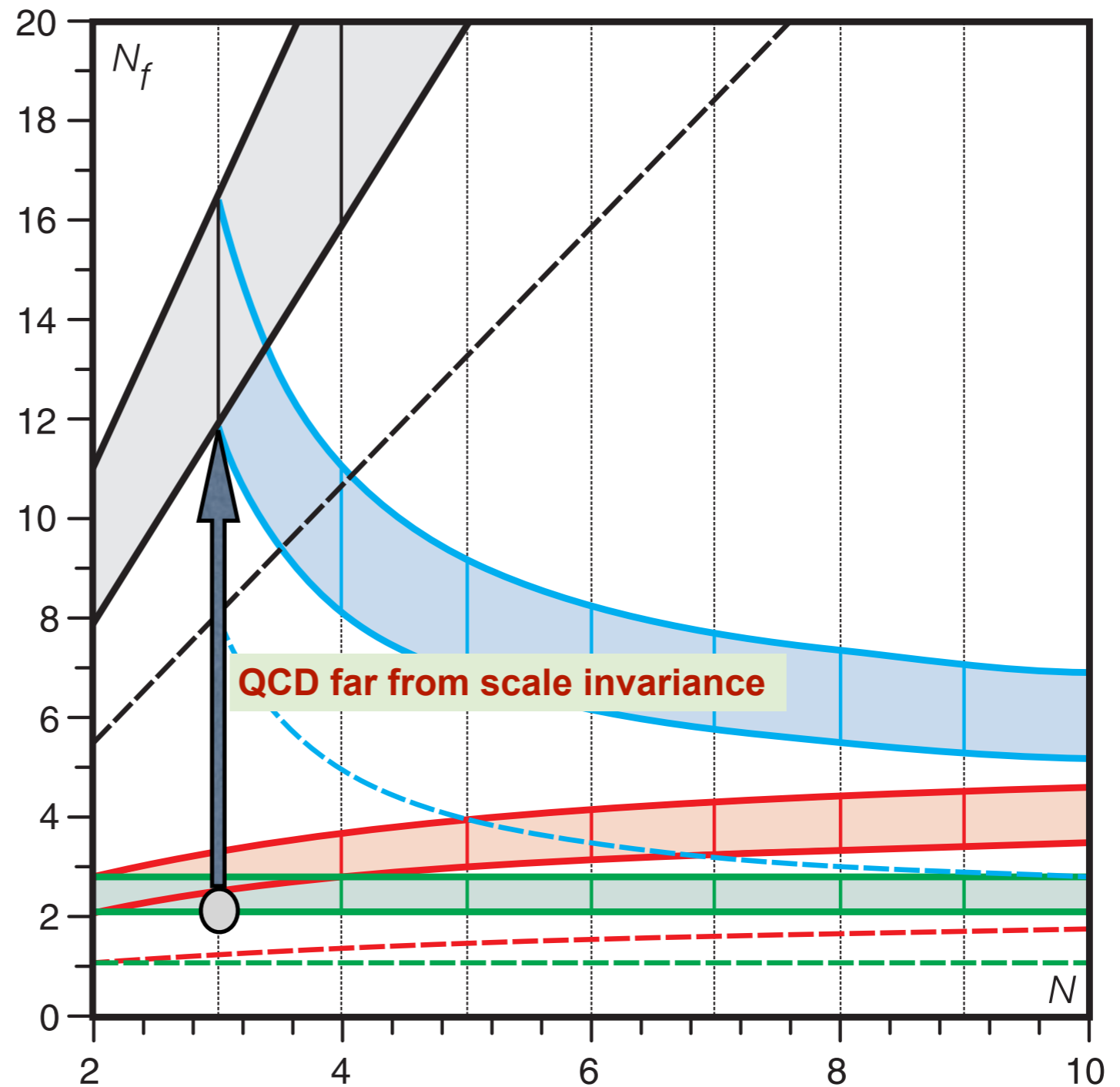anomalous dimension

Early universe

EW phase transition
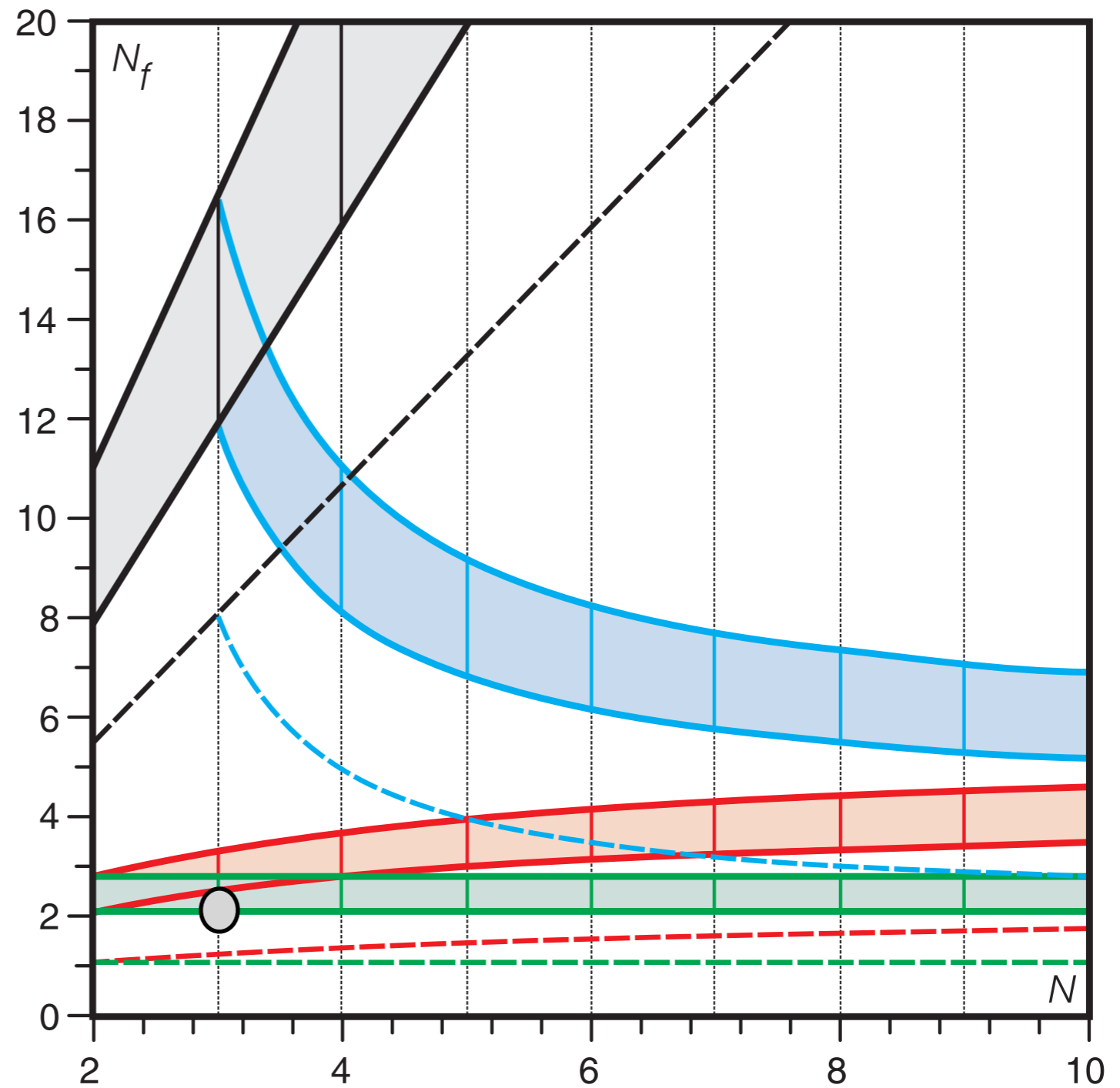dark matter   Mondal 8C Friday

Summary and Outlook

near-conformal light Higgs (dilaton-like?) sextet rep

near-conformal light Higgs (dilaton-like?) sextet rep

QCD far from scale invariance

near-conformal light Higgs (dilaton-like?) sextet rep

near-conformal light Higgs (dilaton-like?) sextet rep
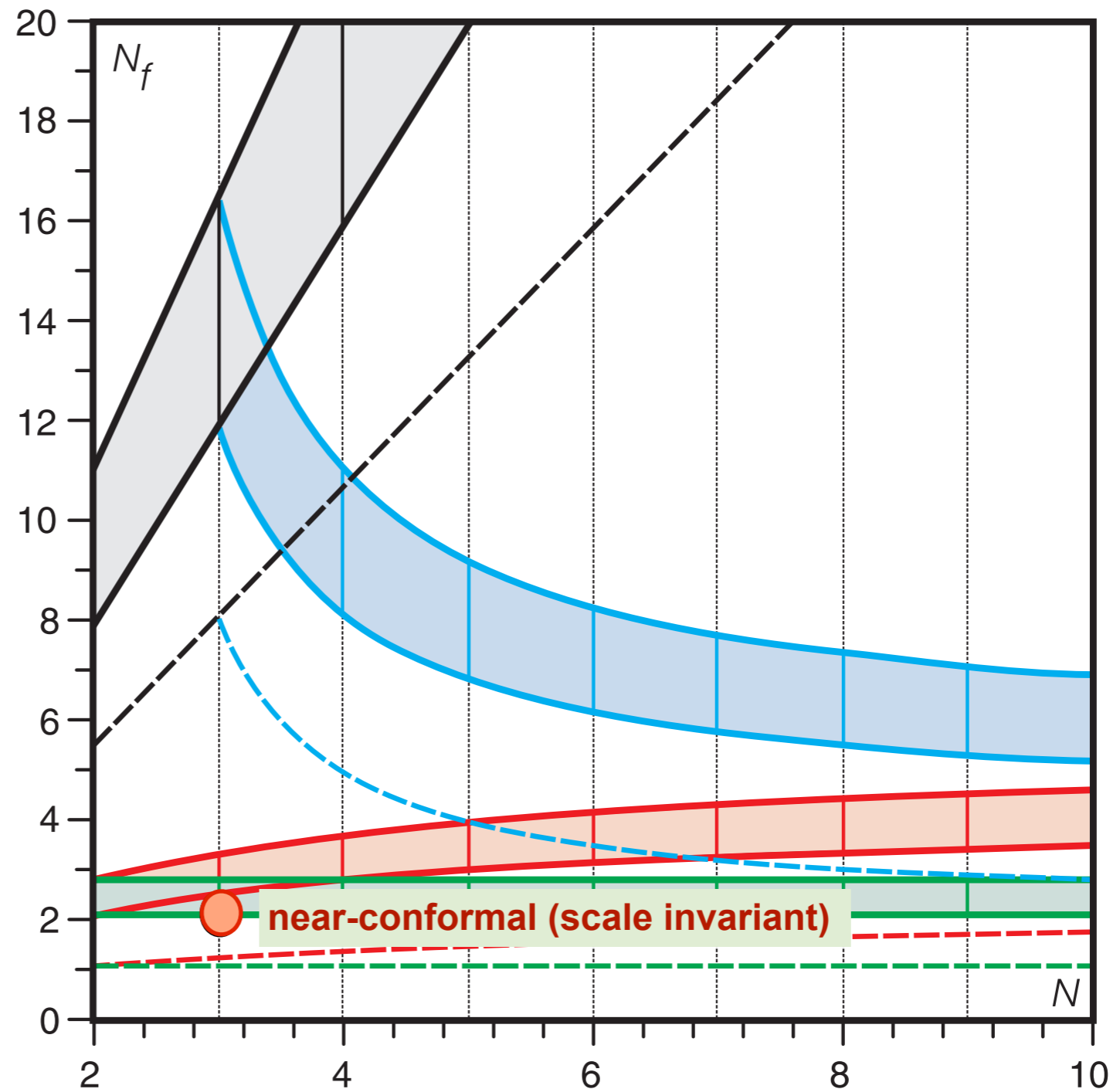
to illustrate: sextet SU(3) color rep

one massless fermion doublet $\begin{bmatrix} u \\ d \end{bmatrix}$

χSB on $\Lambda\sim$TeV scale

three Goldstone pions
become longitudinal
components of weak bosons

composite Higgs mechanism
scale of Higgs condensate
~ F=250 GeV

conflicts with EW constraints?

near-conformal (scale invariant)

N_f

N

near-conformal light Higgs (dilaton-like?) sextet rep

to apply QCD intuition to
near-conformal compositeness
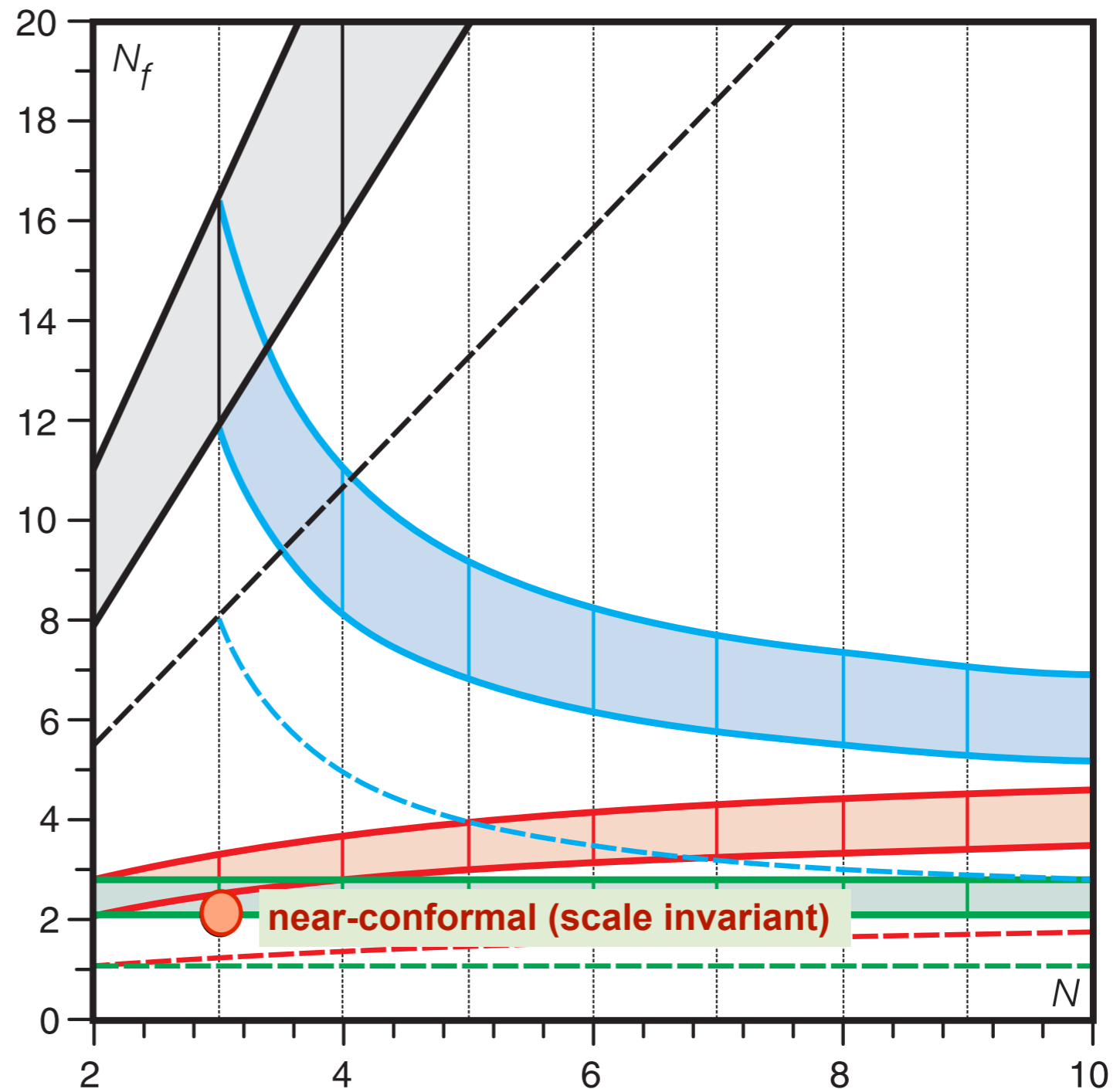is just plain wrong

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near-conformal (scale invariant)

near-conformal light Higgs (dilaton-like?) sextet rep

to apply QCD intuition to near-conformal compositeness is just plain wrong

looking for needle in the haystack, or looking for the haystack?

to illustrate: sextet SU(3) color rep

one massless fermion doublet $\begin{bmatrix} u \\ d \end{bmatrix}$

χSB on $\Lambda \sim$ TeV scale

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looking for needle in the haystack,
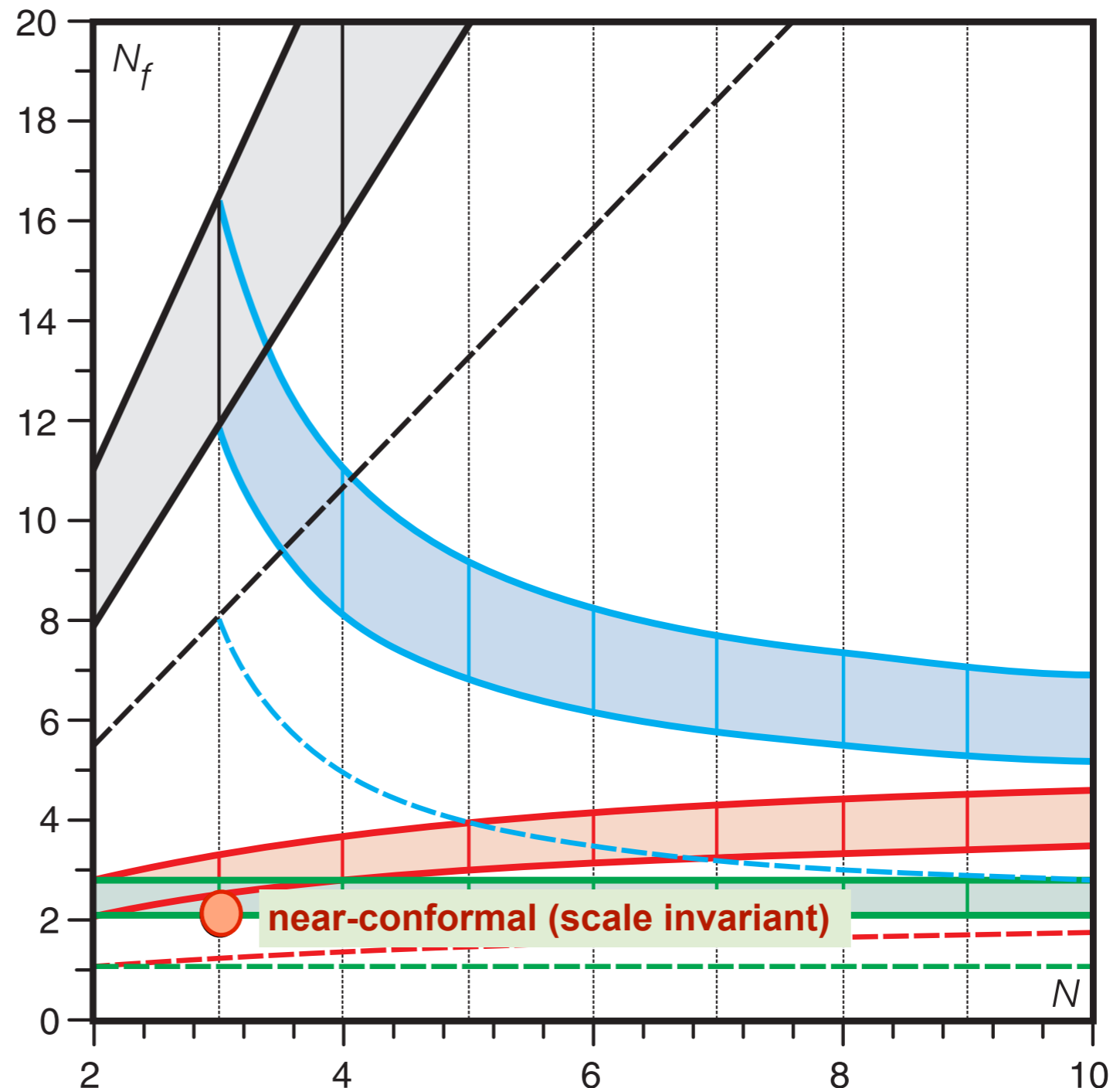or looking for the haystack?

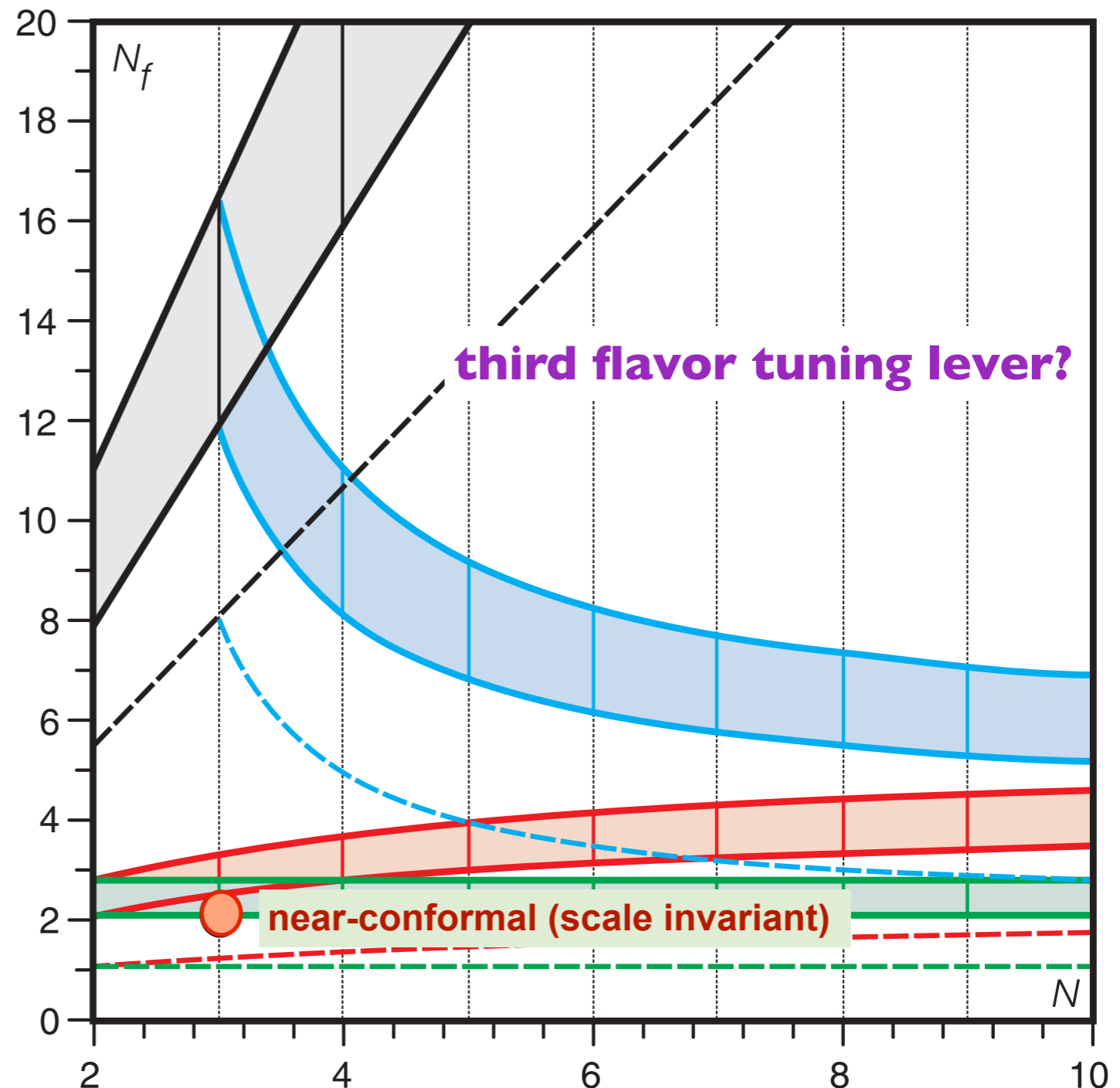**to illustrate: sextet SU(3) color rep**

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χSB on $\Lambda \sim$TeV scale
**three Goldstone pions
become longitudinal
components of weak bosons**

**composite Higgs mechanism
scale of Higgs condensate
$\sim$ F=250 GeV**

conflicts with EW constraints?

third flavor tuning lever?

near-conformal (scale invariant)

near-conformal light Higgs (dilaton-like?) sextet rep

$$m_\sigma^2 \simeq -\frac{4}{f_\sigma^2} \langle 0 | \left[\Theta_\mu^\mu(0) \right]_{NP} | 0 \rangle$$

Partially Conserved Dilatation Current (PCDC)

Will gradient flow based technology make the argument less slippery?

$$\partial_\mu \mathcal{D}^\mu = \Theta_\mu^\mu = \frac{\beta(\alpha)}{4\alpha} G_{\mu\nu}^a G^{a\mu\nu}$$

Dilatation current

Bardeen et al., Ellis, Yamawaki, Miransky, Appelquist, ...

$$\langle 0 | \Theta^{\mu\nu}(x) | \sigma(p) \rangle = \frac{f_\sigma}{3} (p^\mu p^\nu - g^{\mu\nu} p^2) e^{-ipx}$$

$$\langle 0 | \partial_\mu \mathcal{D}^\mu(x) | \sigma(p) \rangle = f_\sigma m_\sigma^2 e^{-ipx}$$

$$\left[\Theta_\mu^\mu \right]_{NP} = \frac{\beta(\alpha)}{4\alpha} \left[G_{\mu\nu}^a G^{a\mu\nu} \right]_{NP} \qquad \frac{m_\sigma}{f_\sigma} \longrightarrow ?$$

near-conformal light Higgs (dilaton-like?) sextet rep

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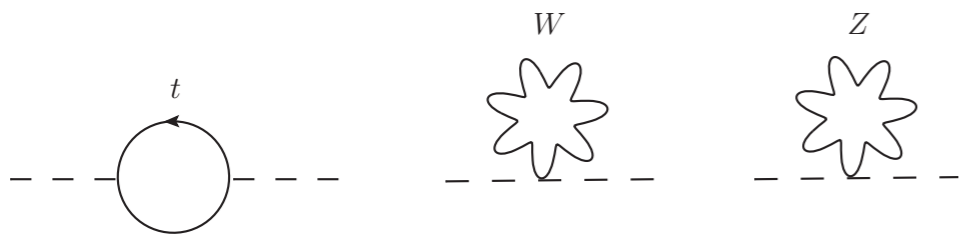$$\langle 0|\partial_\mu \mathcal{D}^\mu(x)|\sigma(p)\rangle = f_\sigma m_\sigma^2 e^{-ipx}$$

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light composite scalar, but how light is light ?

few hundred GeV Higgs impostor?

Foadi, Fransden, Sannino
open for spirited theory discussions

$$\delta M_H^2 \sim -12\kappa^2 r_t^2 m_t^2 \sim -\kappa^2 r_t^2 (600\,\text{GeV})^2$$

5

near-conformal light Higgs (dilaton-like?) sextet rep

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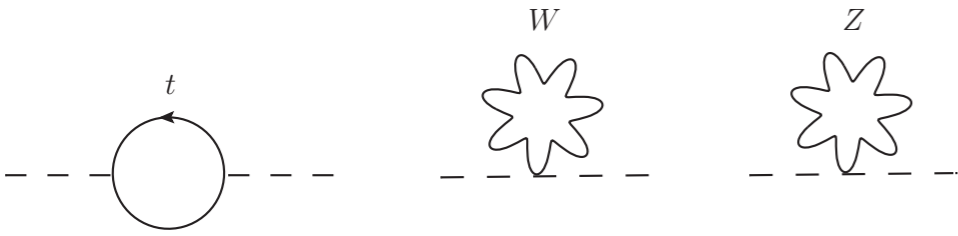
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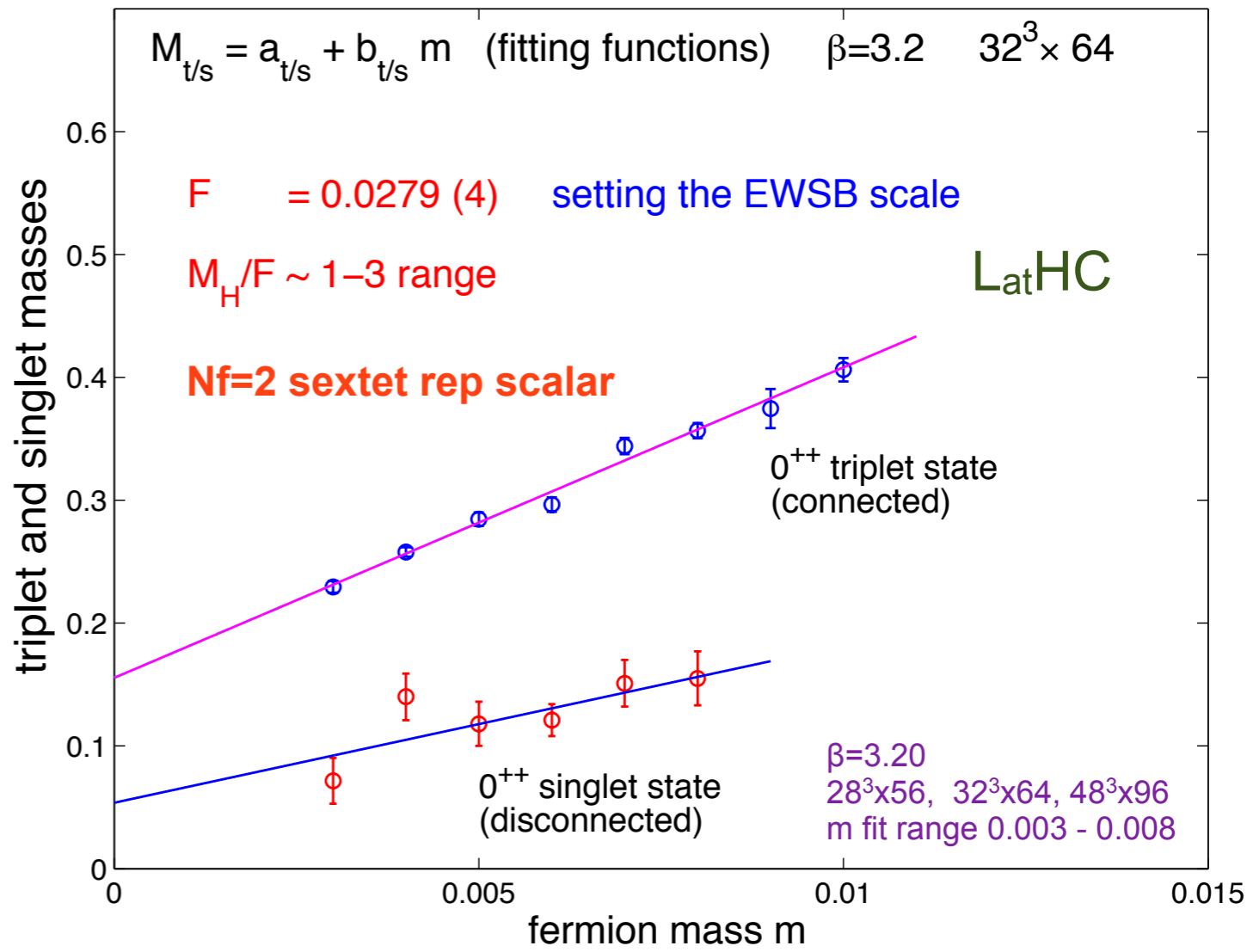
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Triplet and singlet masses from 0^{++} correlators

$M_{t/s} = a_{t/s} + b_{t/s}\, m$ (fitting functions) $\quad \beta=3.2 \quad 32^3 \times 64$

F = 0.0279 (4) setting the EWSB scale

$M_H/F \sim 1\text{--}3$ range

L$_{at}$HC

Nf=2 sextet rep scalar

0^{++} triplet state (connected)

0^{++} singlet state (disconnected)

β=3.20
$28^3 \times 56$, $32^3 \times 64$, $48^3 \times 96$
m fit range 0.003 - 0.008

triplet and singlet masses

fermion mass m

5

near-conformal light Higgs (dilaton-like?) sextet rep

$$m_\sigma^2 \simeq -\frac{4}{f_\sigma^2}\langle 0|\big[\Theta_\mu^\mu(0)\big]_{NP}|0\rangle$$

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Will gradient flow based technology make the argument less slippery?

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Bardeen et al., Ellis, Yamawaki, Miransky, Appelquist, ...

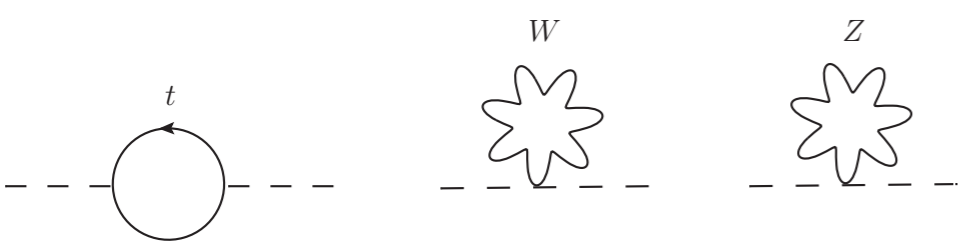"just a light scalar on the lattice, or perhaps dilaton like" ?

We started a second generation run set

first results in Wong's talk

light composite scalar, but
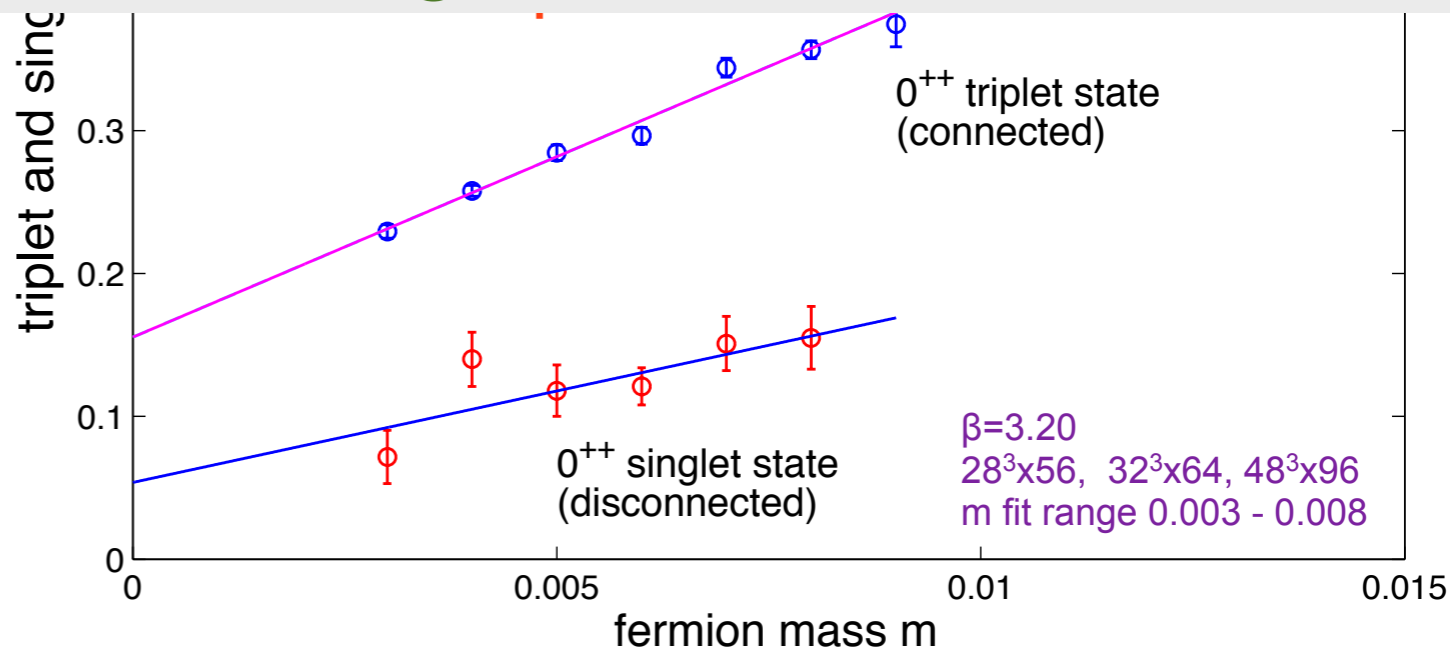**how light is light ?**

few hundred GeV Higgs impostor?

Foadi, Fransden, Sannino
open for spirited theory discussions

$$\delta M_H^2 \sim -12\kappa^2 r_t^2 m_t^2 \sim -\kappa^2 r_t^2 (600\,\text{GeV})^2$$

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(connected)

0^{++} singlet state
(disconnected)

β=3.20
28^{3}x56, 32^{3}x64, 48^{3}x96
m fit range 0.003 - 0.008

triplet and sing...

fermion mass m

new code (sextet Janos) is highly optimized   Borsanyi/Wong effort
In production now to answer important questions in second generation run set:

1. Test of chiral perturbation theory below the scale of low mass scalar?

requires new effective action

how to test if light scalar is dilaton-like? effective theory of dilaton?
RMT and Dirac spectral density on two scales (m and λ)

2. Needs precise scale setting and resonance spectrum

S and T parameters of Electroweak precision tests
large volumes **F · L ~ 1, or larger!**

slow topology?

We are in a second generation run set

β=3.15, 3.20, 3.25, 3.30 gauge couplings

48^3x96, 40^3x80, 32^3x64   volumes

3. Running (walking?) coupling

volume-dependent running coupling
scale-dependent L= ∞ coupling in chiral limit

at least 3 fermion masses in each run

eventually we might need some L=64 runs

4. Consistent chiral condensate?

GMOR relation is still not quite consistent
new method for spectral density and mode number
anomalous dimension of chiral condensate
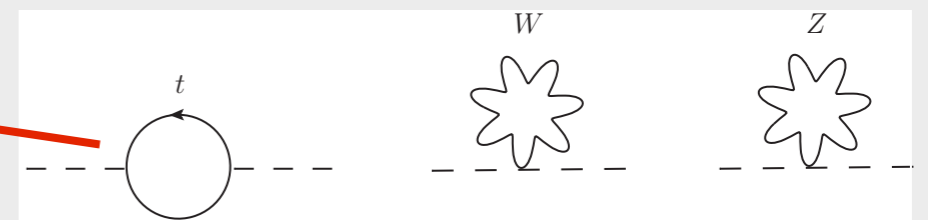dependence on topology

TeV

N ~ 3.2 TeV

A_1 ~ 2.7 TeV

Rho ~ 1.9 TeV

A_0 ~ 1.7 TeV

near-conformal resonance spectrum
separated from light scalar

within LHC14 reach

Wong's talk

scalar impostor few hundred GeV?
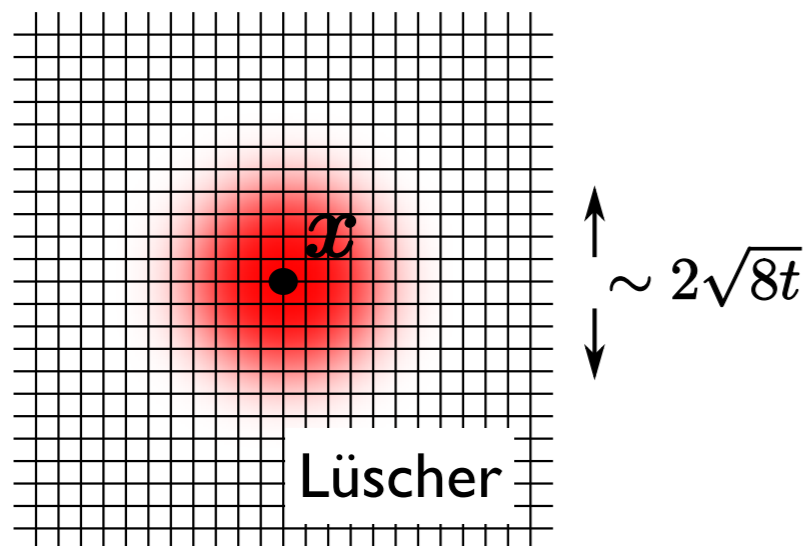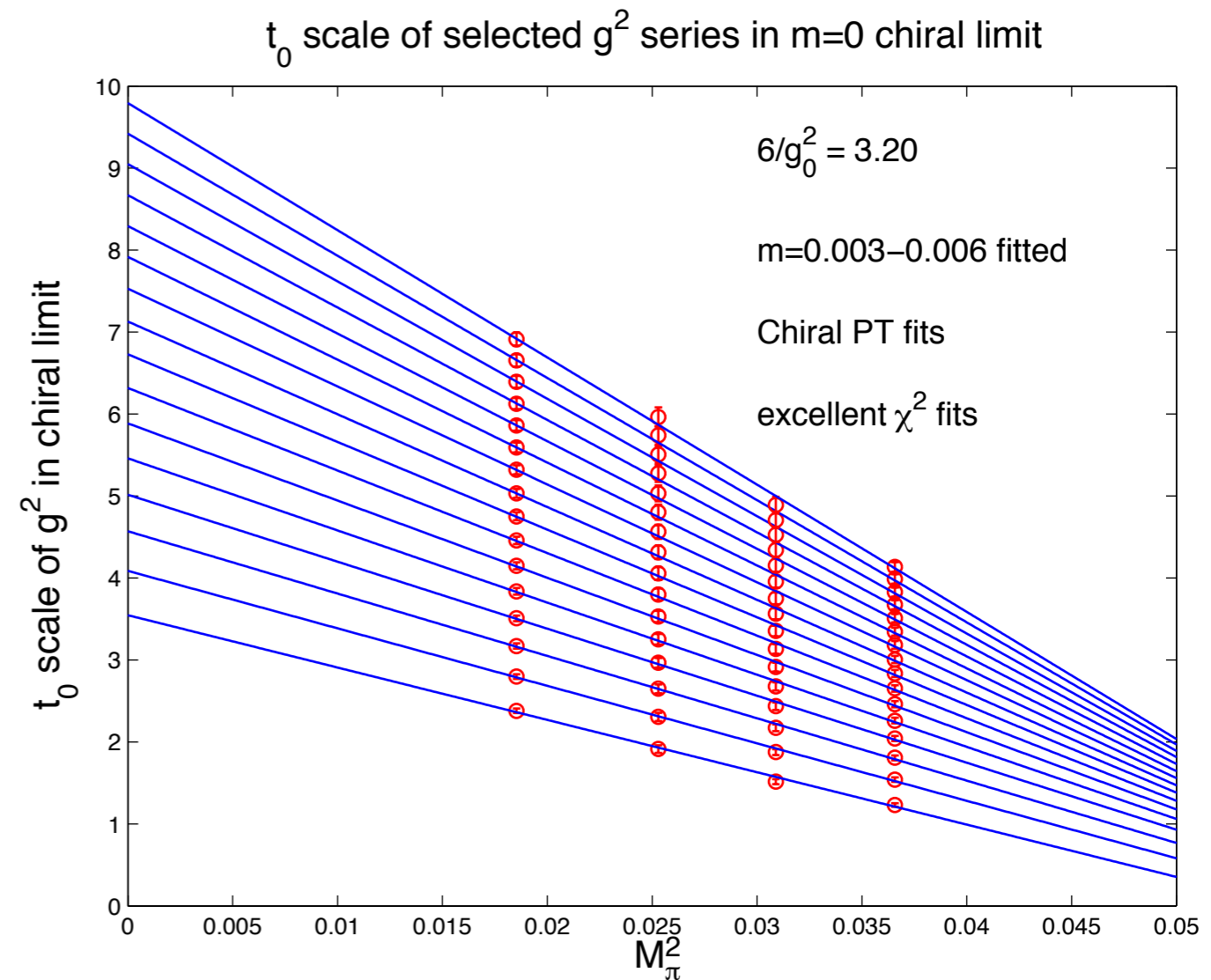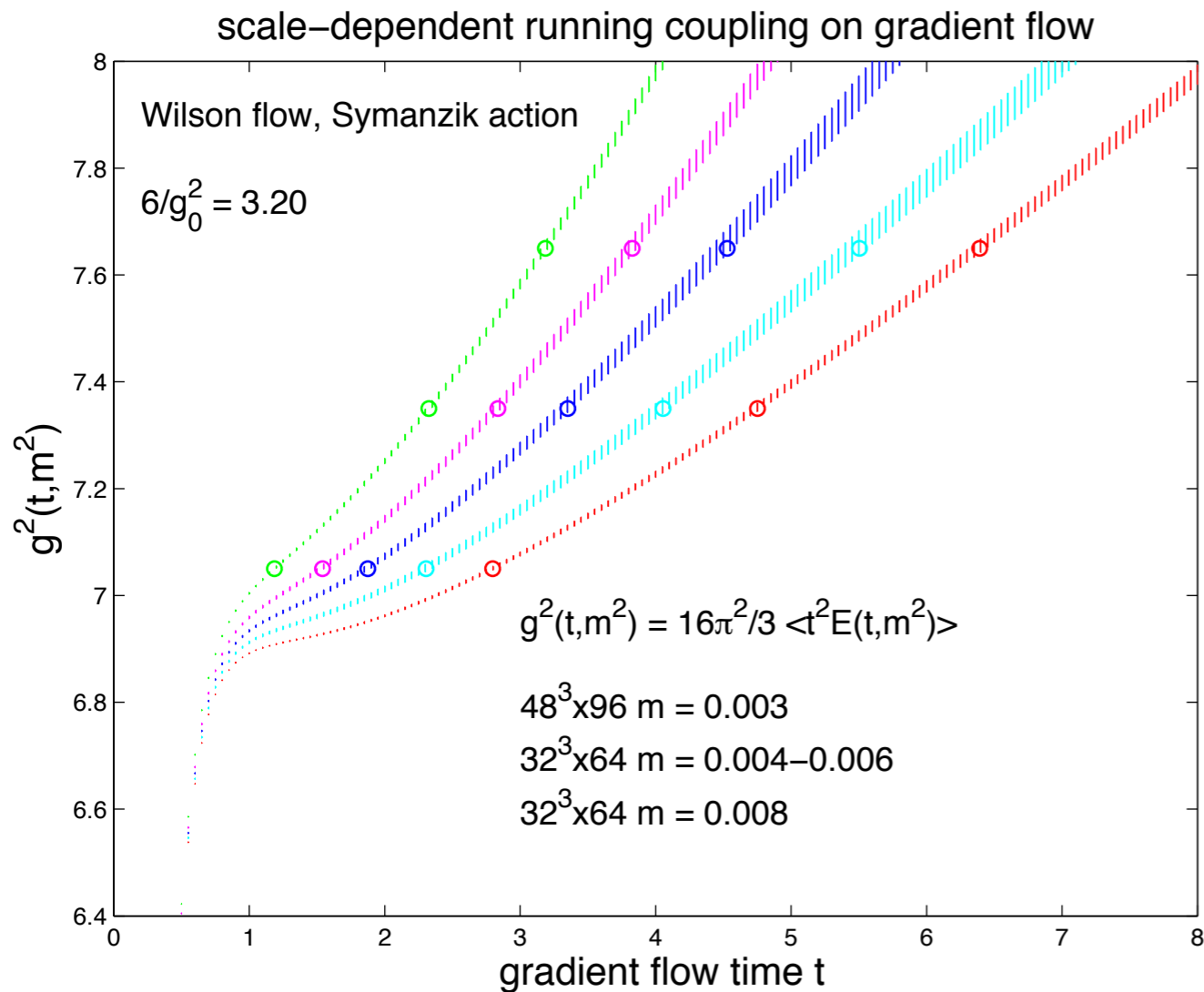
EW self-energy shift

observed Higgs-like?

$$\delta M_H^2 \ \sim \ -12\kappa^2 r_t^2 m_t^2 \ \sim \ -\kappa^2 r_t^2 (600\,\text{GeV})^2$$

We are in a second generation run set pushing the resonance spectrum
somewhat higher

running coupling and beta function from gradient flow   sextet rep

scale−dependent running coupling on gradient flow

Wilson flow, Symanzik action

$6/g_0^2 = 3.20$

$g^2(t,m^2) = 16\pi^2/3 \langle t^2 E(t,m^2)\rangle$

$48^3 \times 96$ m = 0.003
$32^3 \times 64$ m = 0.004−0.006
$32^3 \times 64$ m = 0.008

y-axis: $g^2(t,m^2)$

x-axis: gradient flow time t

t_0 scale of selected g^2 series in m=0 chiral limit

$6/g_0^2 = 3.20$

m=0.003−0.006 fitted

Chiral PT fits

excellent χ^2 fits

y-axis: t_0 scale of g^2 in chiral limit

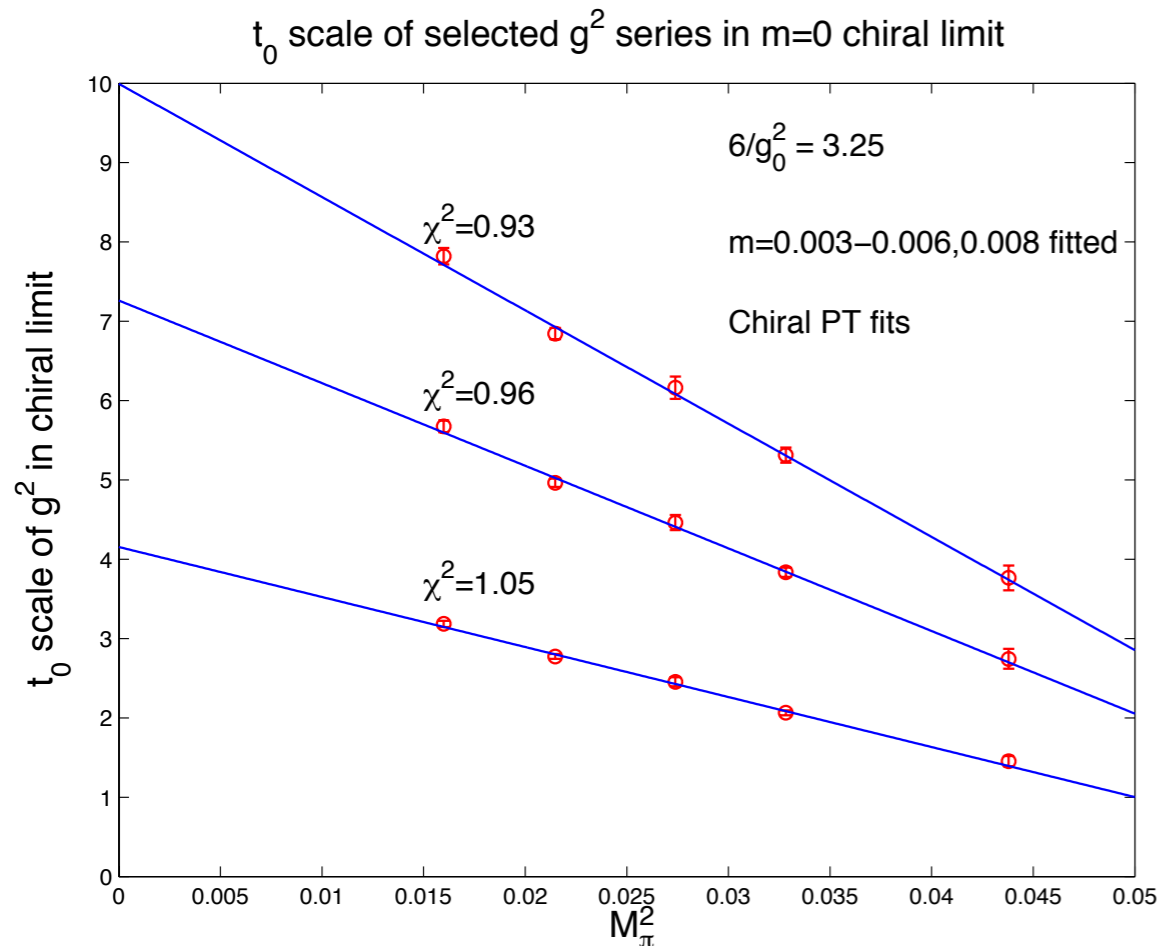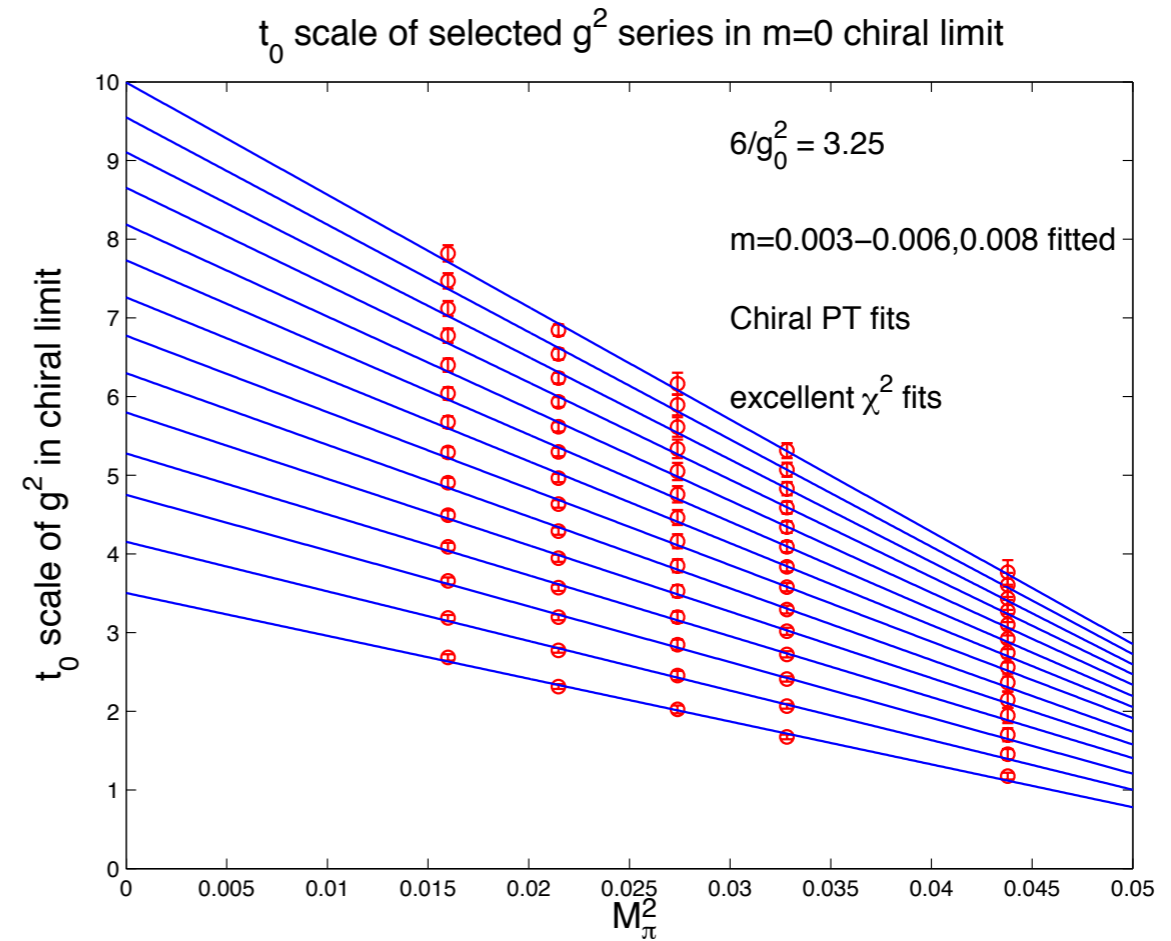x-axis: M_π^2
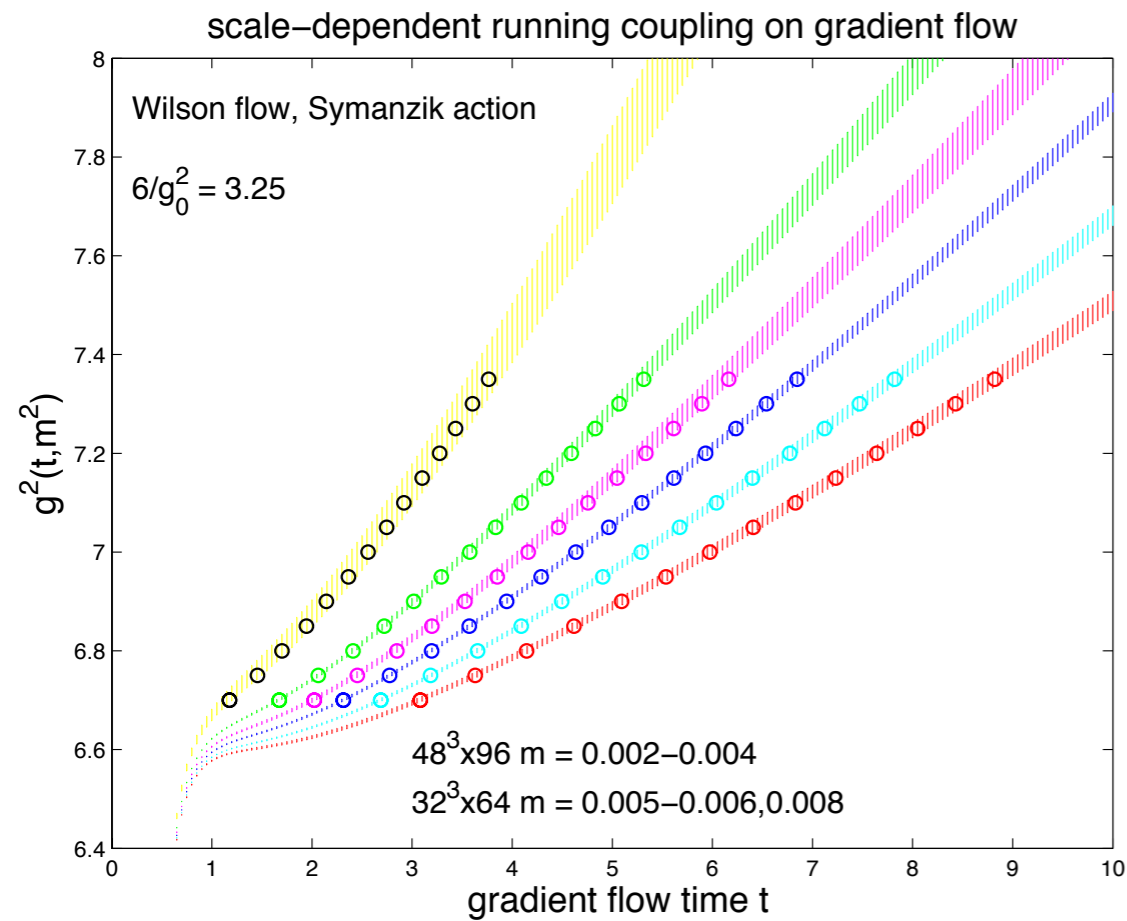
$\sim 2\sqrt{8t}$

x

Lüscher

operator is quasi-point source of pions

controlled in chiPT

Bär and Golterman

fits of leading chiPT are excellent

running coupling and beta function from gradient flow   sextet rep

scale−dependent running coupling on gradient flow

Wilson flow, Symanzik action

$6/g_0^2 = 3.25$

$48^3 \times 96$ m = 0.002−0.004
$32^3 \times 64$ m = 0.005−0.006,0.008

x-axis: gradient flow time t
y-axis: $g^2(t,m^2)$

t_0 scale of selected g^2 series in m=0 chiral limit

$6/g_0^2 = 3.25$

m=0.003−0.006,0.008 fitted

Chiral PT fits

excellent χ^2 fits

x-axis: M_π^2
y-axis: t_0 scale of g^2 in chiral limit

t_0 scale of selected g^2 series in m=0 chiral limit

$6/g_0^2 = 3.25$

m=0.003−0.006,0.008 fitted

Chiral PT fits

$\chi^2 = 0.93$
$\chi^2 = 0.96$
$\chi^2 = 1.05$

x-axis: M_π^2
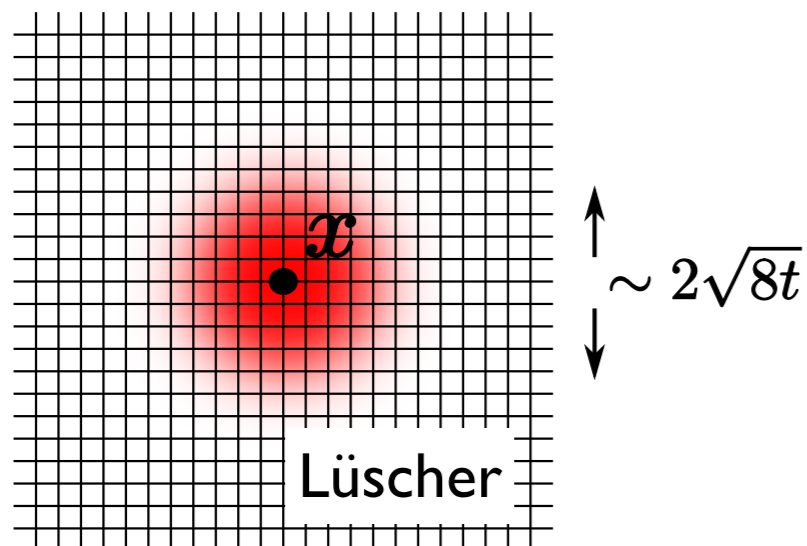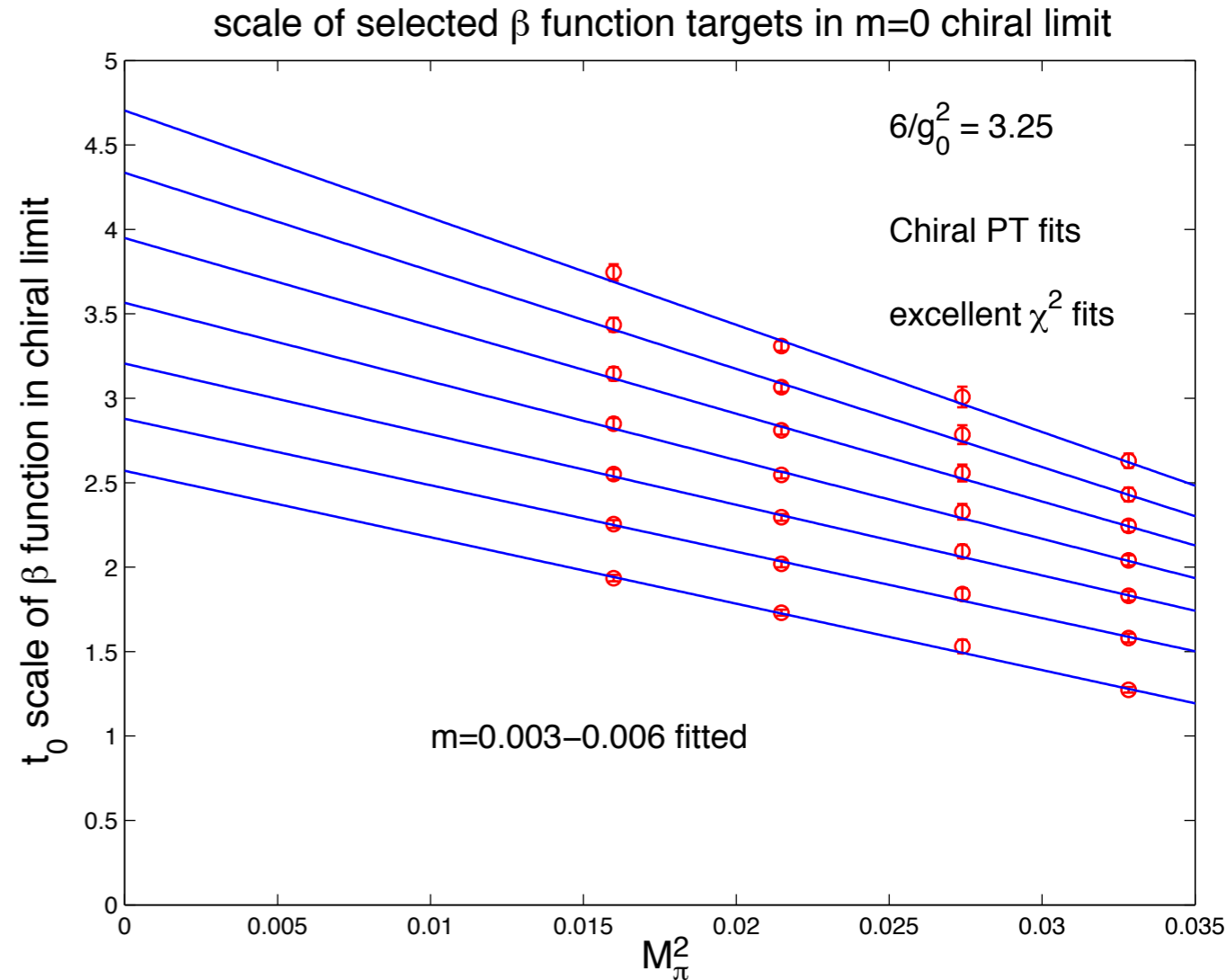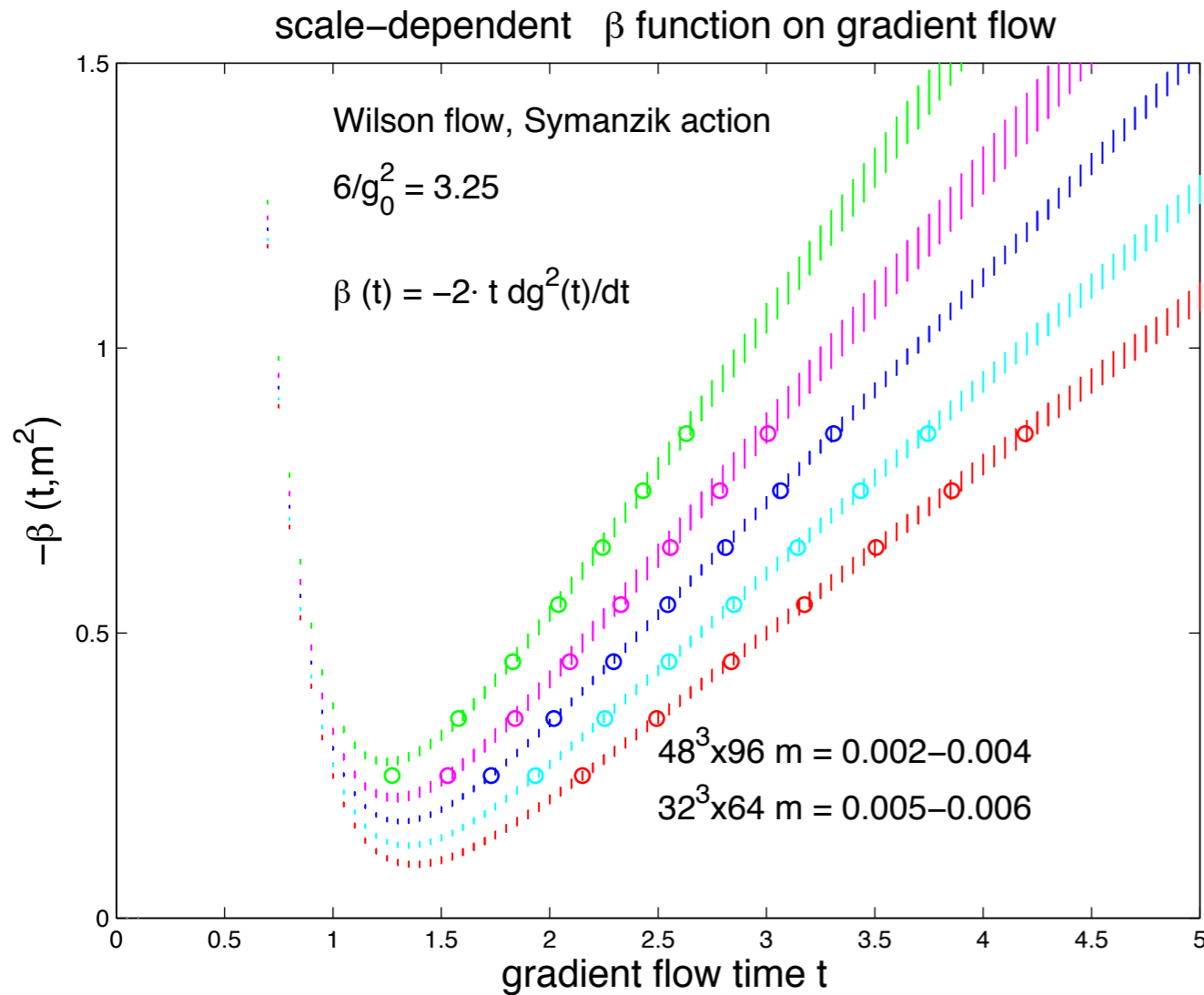y-axis: t_0 scale of g^2 in chiral limit

this is the second run set at $6/g_0^2 = 3.25$

two other sets at $6/g_0^2 = 3.15$ and $6/g_0^2 = 3.30$ are in the works

fits of leading chiPT are excellent

running coupling and beta function from gradient flow   sextet rep

scale-dependent β function on gradient flow

Wilson flow, Symanzik action

$6/g_0^2 = 3.25$

$\beta(t) = -2 \cdot t \, dg^2(t)/dt$

$48^3 \times 96 \; m = 0.002-0.004$

$32^3 \times 64 \; m = 0.005-0.006$

$-\beta(t, m^2)$ vs gradient flow time t

scale of selected β function targets in m=0 chiral limit

$6/g_0^2 = 3.25$

Chiral PT fits

excellent χ^2 fits

$m = 0.003-0.006$ fitted

t_0 scale of β function in chiral limit vs M_π^2

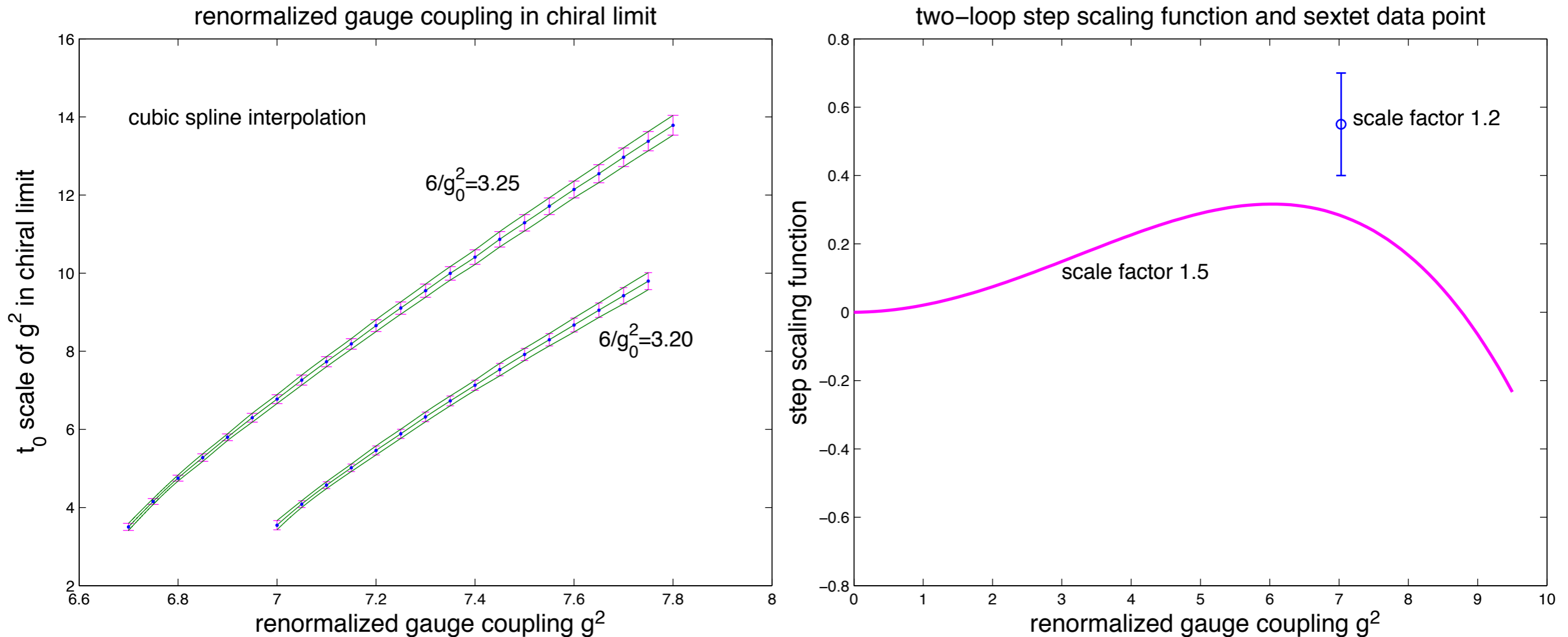$\sim 2\sqrt{8t}$

Lüscher

cross check on direct beta function at $6/g_0^2 = 3.25$

$\sim W_0$ of Wuppertal group

fits of leading chiPT are excellent again

running coupling and beta function from gradient flow   sextet rep

renormalized gauge coupling in chiral limit

two–loop step scaling function and sextet data point

step function is larger than 2-loop (walking regime may or may not exist)

will have to be matched to perturbative running of finite volume $g^2(L)$

will tree-level improved analysis help when the operator is expanded in leading order of g^2 :

$$\langle t^2 E(t)\rangle = g_0^2 t^2 \int_{-\frac{\pi}{a}}^{\frac{\pi}{a}} \frac{d^4 p}{(2\pi)^4} \mathrm{Tr}\left(e^{-t(\mathcal{S}^f+\mathcal{G})}(\mathcal{S}^g + \mathcal{G})^{-1} e^{-t(\mathcal{S}^f+\mathcal{G})}\mathcal{S}^e\right)$$
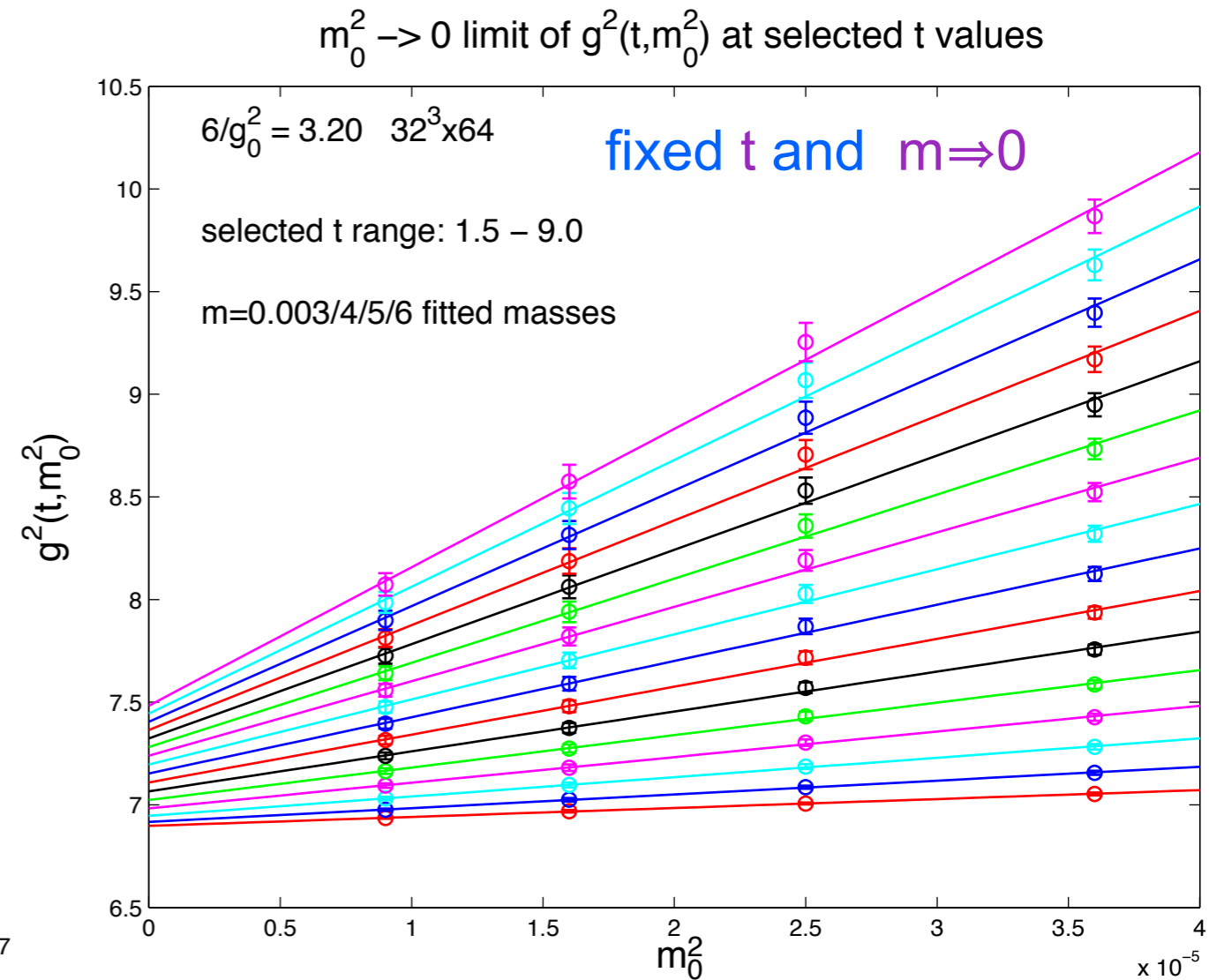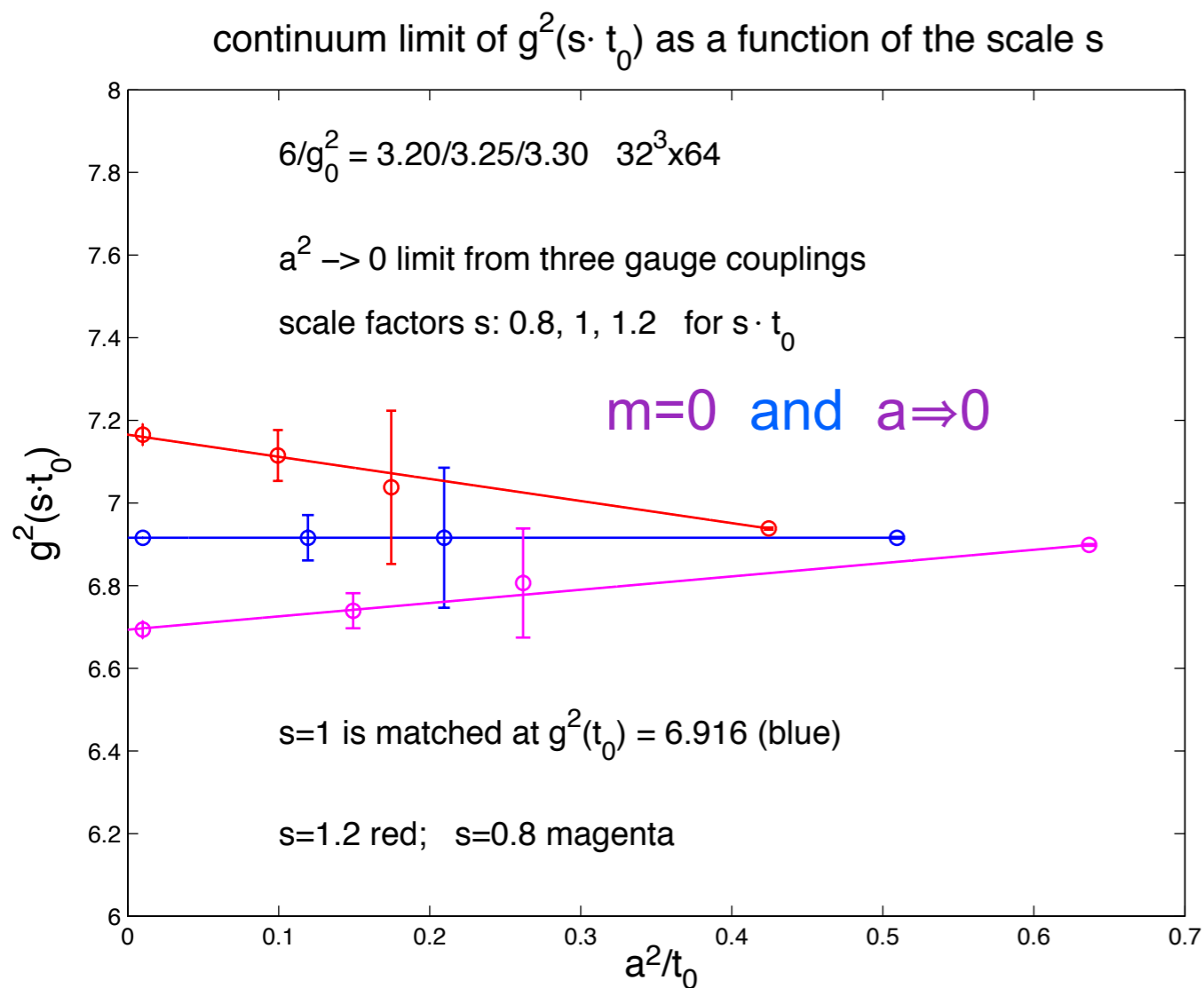
Nogradi 7E Thursday

running coupling and beta function from gradient flow   sextet rep

complementing the analysis is the PT motivated procedure   (JK SCGT14mini talk)
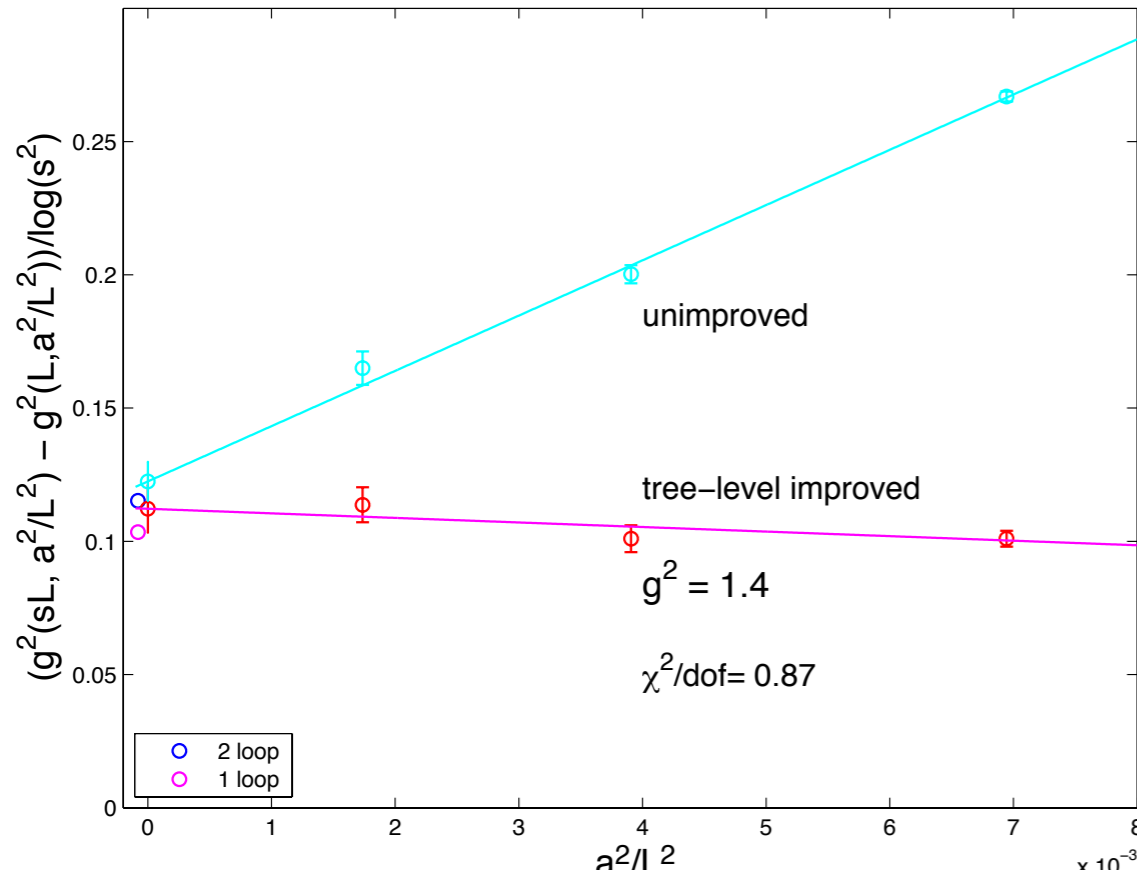
fixed t m2 -> 0 extrapolation (3 gauge couplings)

results give a somewhat lower step scaling function, closer to walking
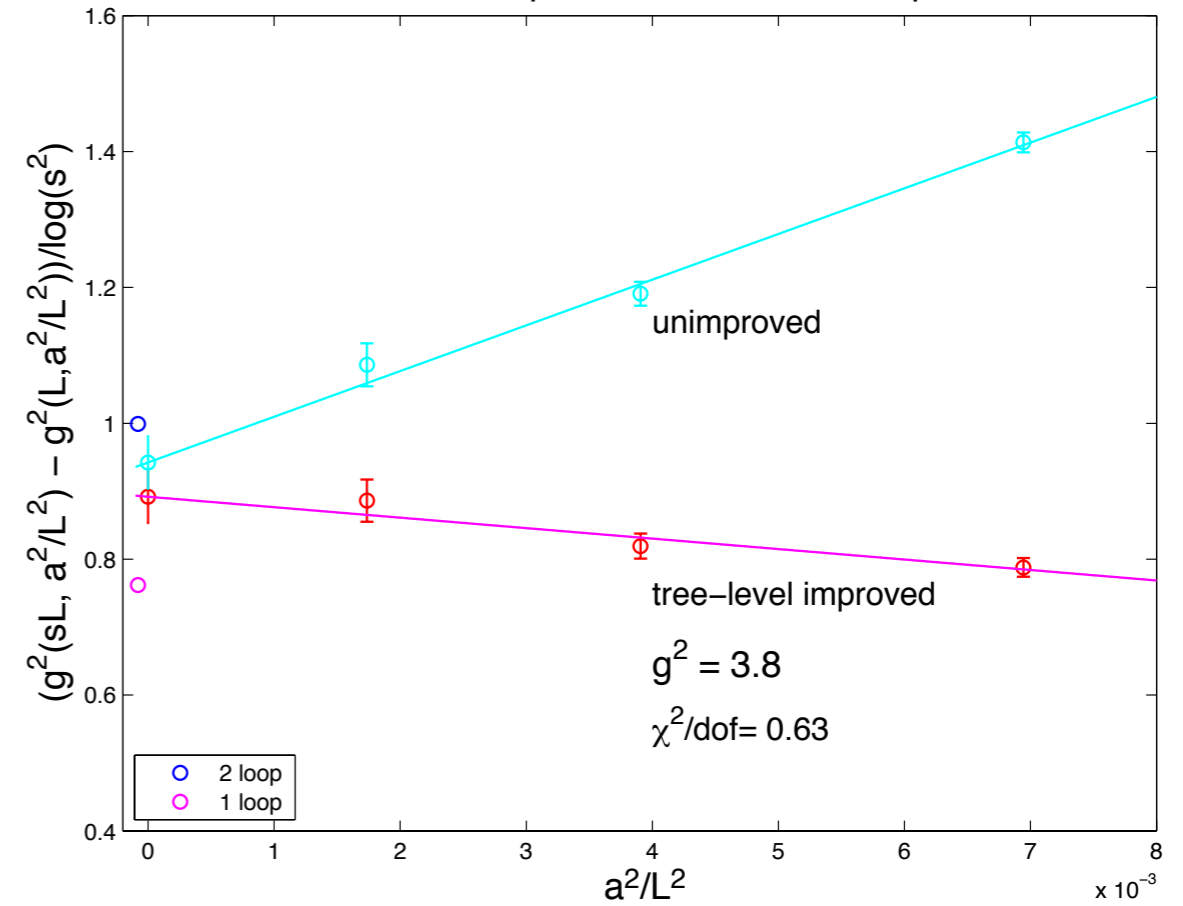systematics to clean in both procedures

continuum limit of $g^2(s \cdot t_0)$ as a function of the scale s

$6/g_0^2 = 3.20/3.25/3.30$ $32^3 \times 64$

$a^2 \to 0$ limit from three gauge couplings

scale factors s: 0.8, 1, 1.2   for $s \cdot t_0$

m=0 and a⇒0

s=1 is matched at $g^2(t_0) = 6.916$ (blue)

s=1.2 red;   s=0.8 magenta

$m_0^2 \to 0$ limit of $g^2(t, m_0^2)$ at selected t values

$6/g_0^2 = 3.20$ $32^3 \times 64$

fixed t and m⇒0

selected t range: 1.5 – 9.0

m=0.003/4/5/6 fitted masses

running coupling and beta function from gradient flow   sextet rep
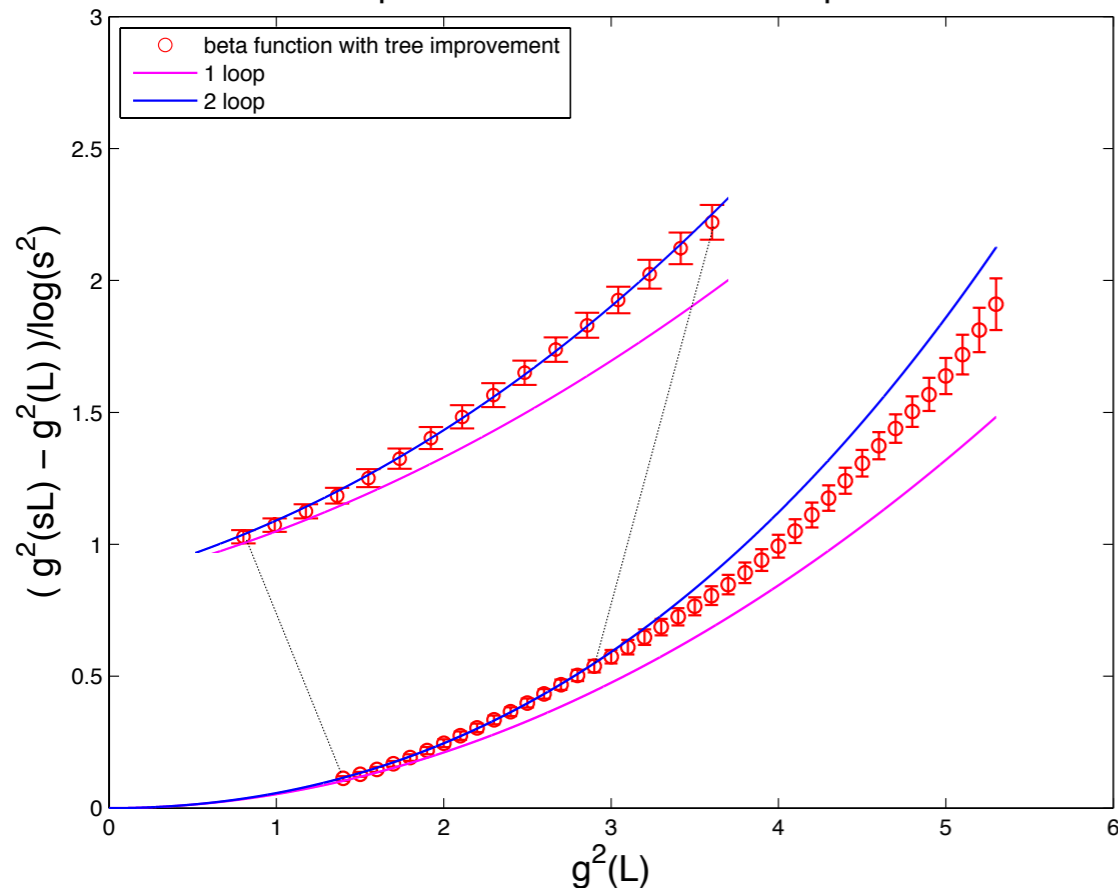

works very well in Nf=4 fundamental rep test

sextet rep and Nf=8,12 fundamental reps are in the works

The chiral (Higgs) condensate

- New stochastic method

- Direct determination of full spectral density and mode number distribution on gauge configurations

- To remove UV divergences at finite fermion mass

- To investigate internal (in)consistencies with GMOR relation

- To determine anomalous dimension of the chiral condensate

- To investigate dependence on slowly changing topology

The chiral condensate in the sextet theory

- new stochastic method   sextet Nf=2   code developed by Ricky Wong

- direct determination of full spectral density and mode number distribution

- based on Chebyshev polynomial resolution of spectral density

$\pi \cdot \rho(\lambda)$ spectral density of full spectrum

β=3.20   m=0.003

63,700,9992 eigenvalues in D$^+$D
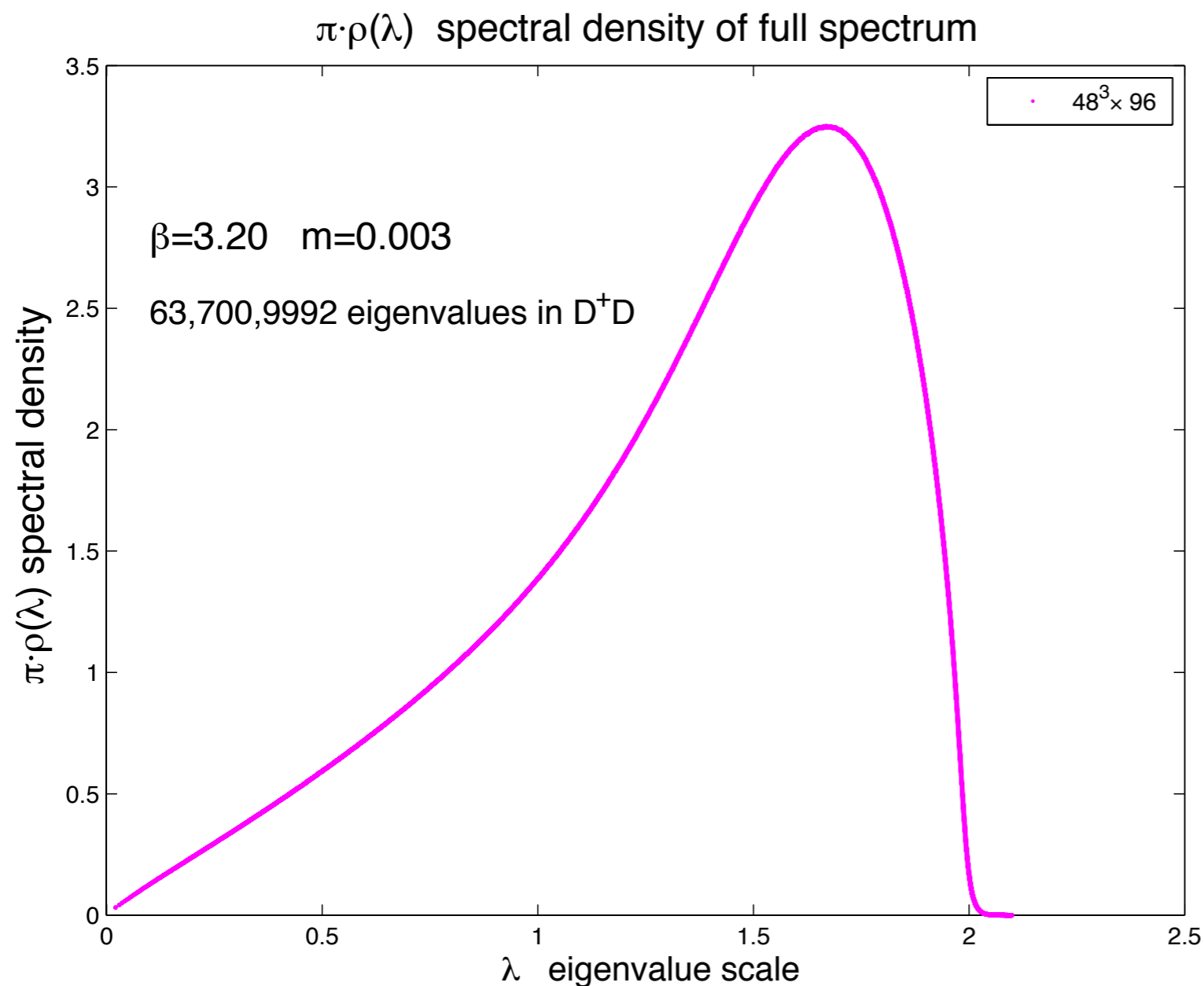
- typically Chebyshev order ~ 3,000

- Passed all tests so far

- example is from 48^{3}x96 lattices

- allows independent variation of
  m and λ extended analysis!

- topology dependence and the
  anomalous dimension of the chiral
  condensate
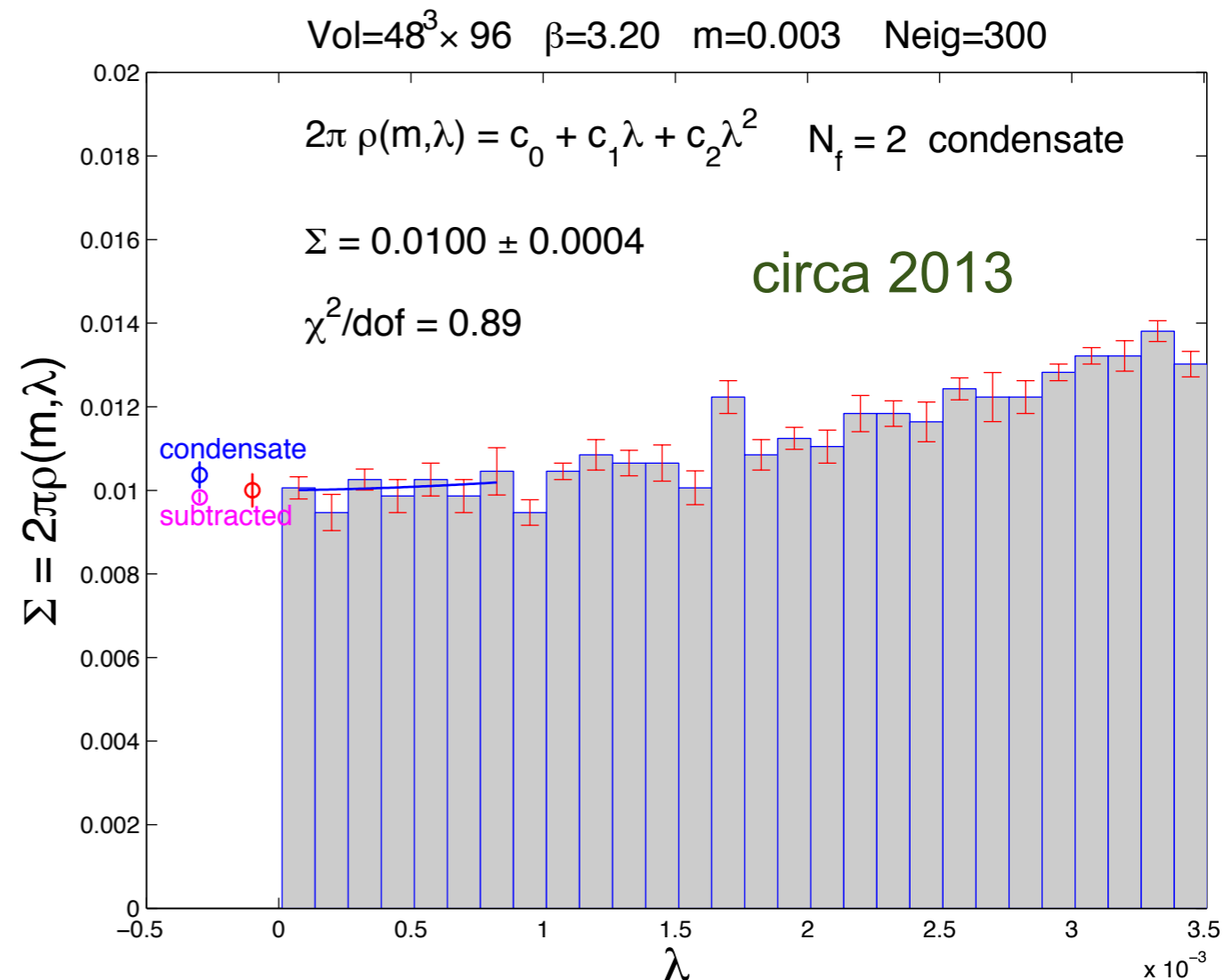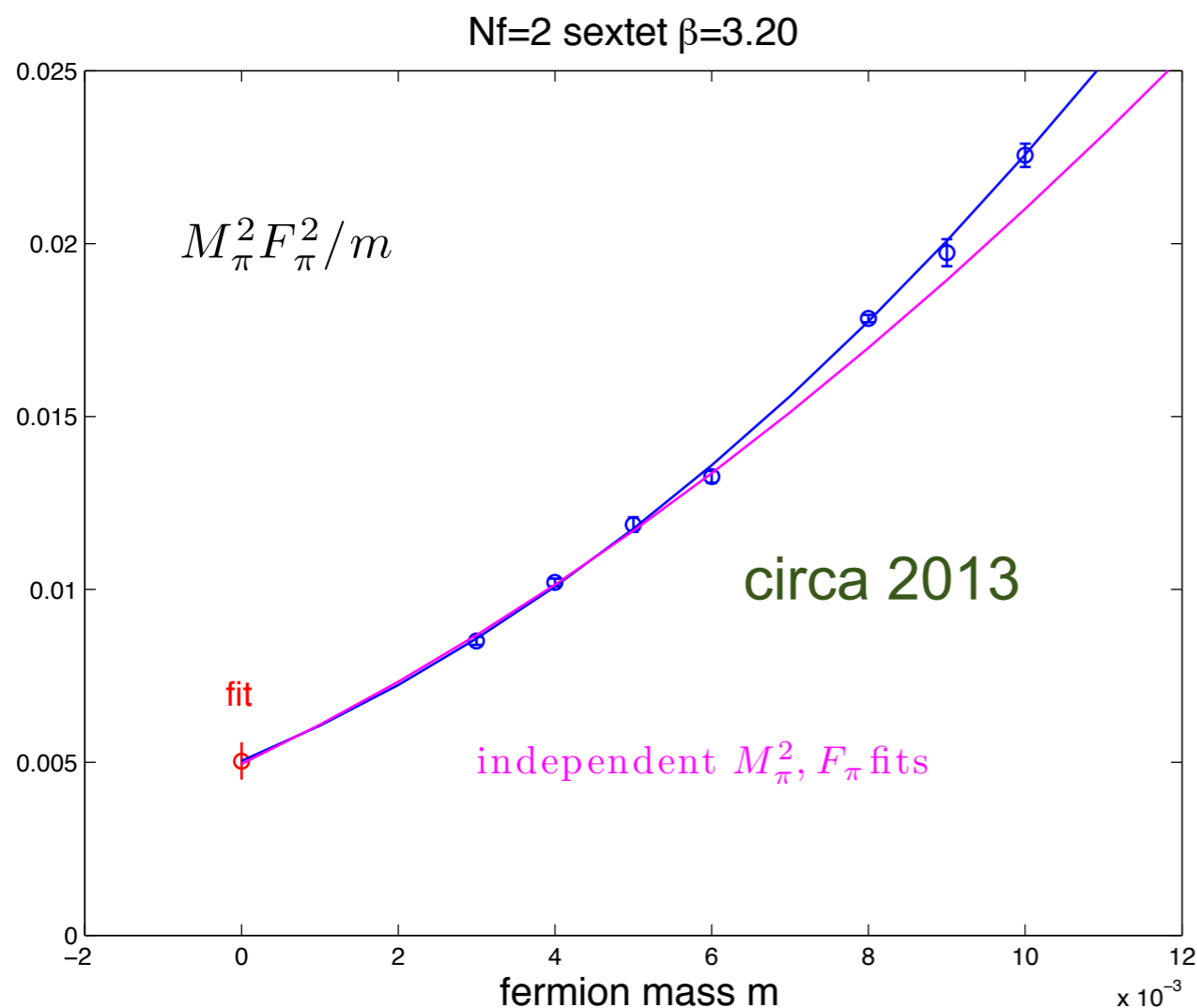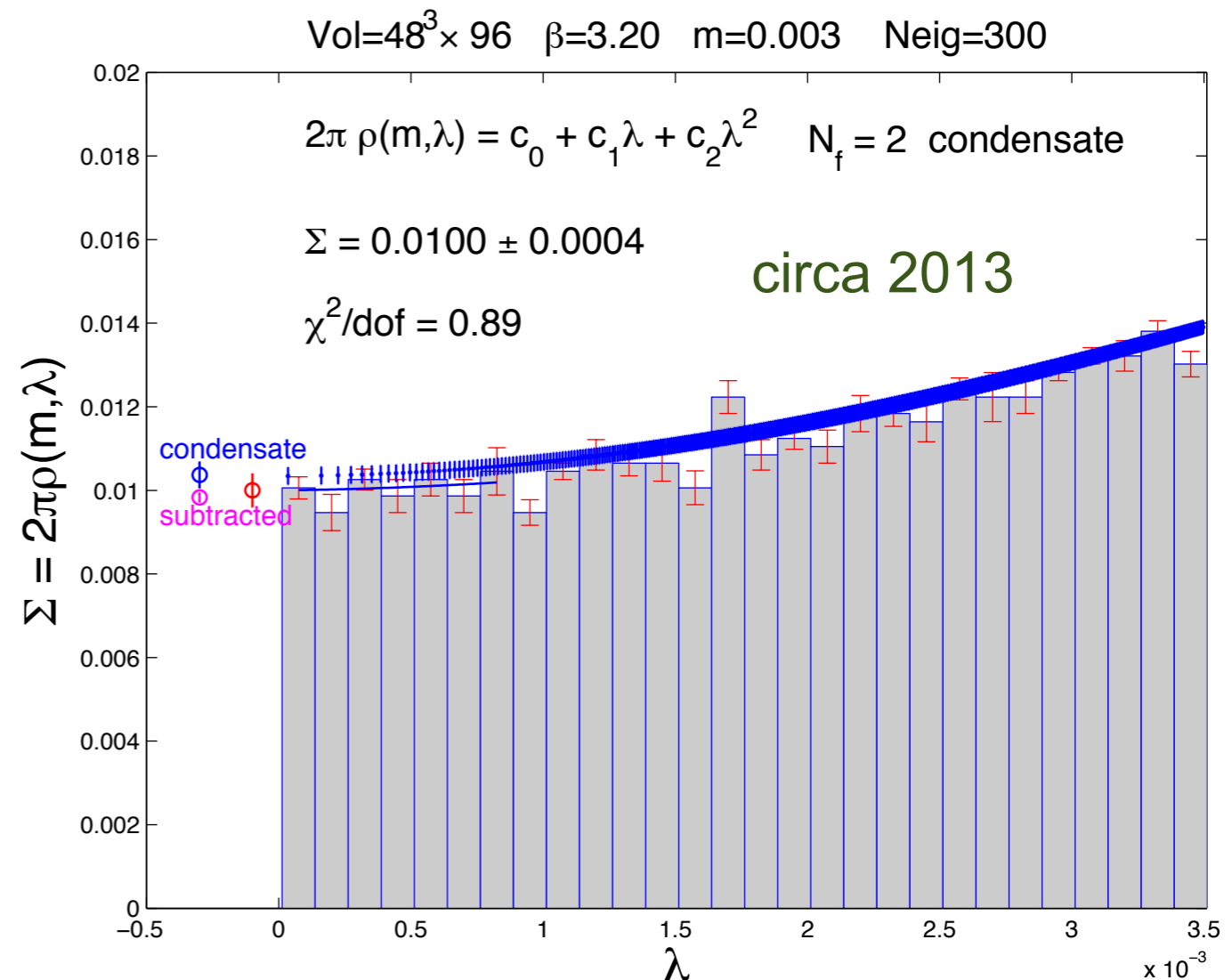
The chiral condensate in the sextet theory

control on UV divergences: mode number density of chiral condensate

$$\rho(\lambda, m) = \frac{1}{V} \sum_{k=1}^{\infty} \langle \delta(\lambda - \lambda_k) \rangle \qquad \lim_{\lambda \to 0} \lim_{m \to 0} \lim_{V \to \infty} \rho(\lambda, m) = \frac{\Sigma}{\pi} \qquad \text{spectral density}$$

$$\nu(M, m) = V \int_{-\Lambda}^{\Lambda} d\lambda\, \rho(\lambda, m), \qquad \Lambda = \sqrt{M^2 - m^2} \qquad \text{mode number density}$$

$$\nu_{\mathrm{R}}(M_{\mathrm{R}}, m_{\mathrm{R}}) = \nu(M, m_{\mathrm{q}}) \qquad \text{renormalized and RG invariant} \qquad \text{(Giusti and Luscher)}$$

Nf=2 sextet β=3.20

$M_\pi^2 F_\pi^2 / m$

fit

independent M_π^2, F_π fits

circa 2013

fermion mass m

Vol=48³× 96   β=3.20   m=0.003   Neig=300

$2\pi \rho(m,\lambda) = c_0 + c_1\lambda + c_2\lambda^2$ $N_f = 2$ condensate

$\Sigma = 0.0100 \pm 0.0004$

$\chi^2/\mathrm{dof} = 0.89$

circa 2013

condensate

subtracted
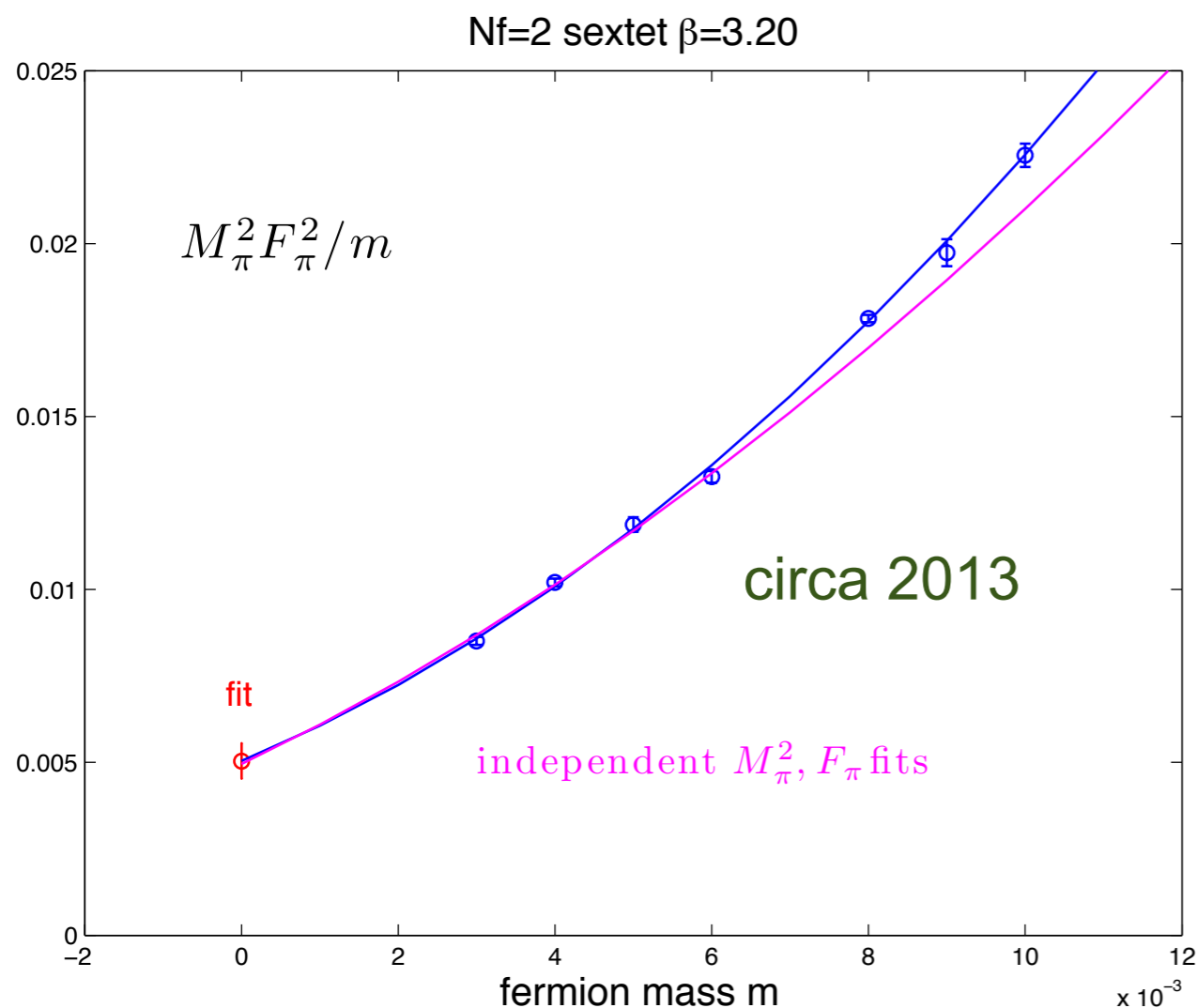
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λ

The chiral condensate in the sextet theory

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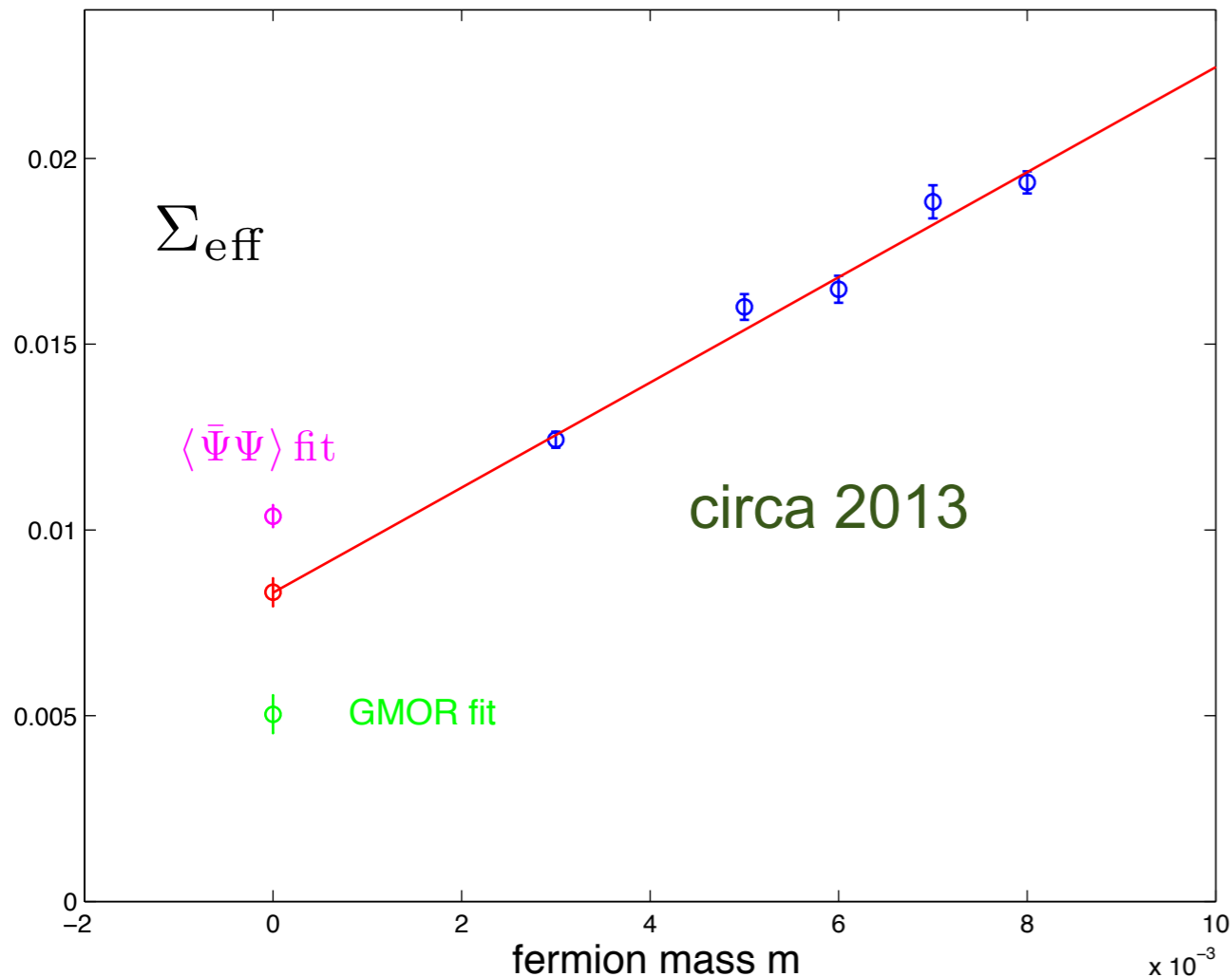
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The chiral condensate in the sextet theory

Nf=2 sextet β=3.20 Λ=0.003

Σ_{eff}

$\langle \bar{\Psi}\Psi \rangle \, \text{fit}$

circa 2013

GMOR fit

fermion mass m   x 10^{-3}

Nf=2 sextet β=3.20 Λ=0.003

Σ_{eff} circa 2013

linear fit

chiral perturbation theory

fermion mass m   x 10^{-3}
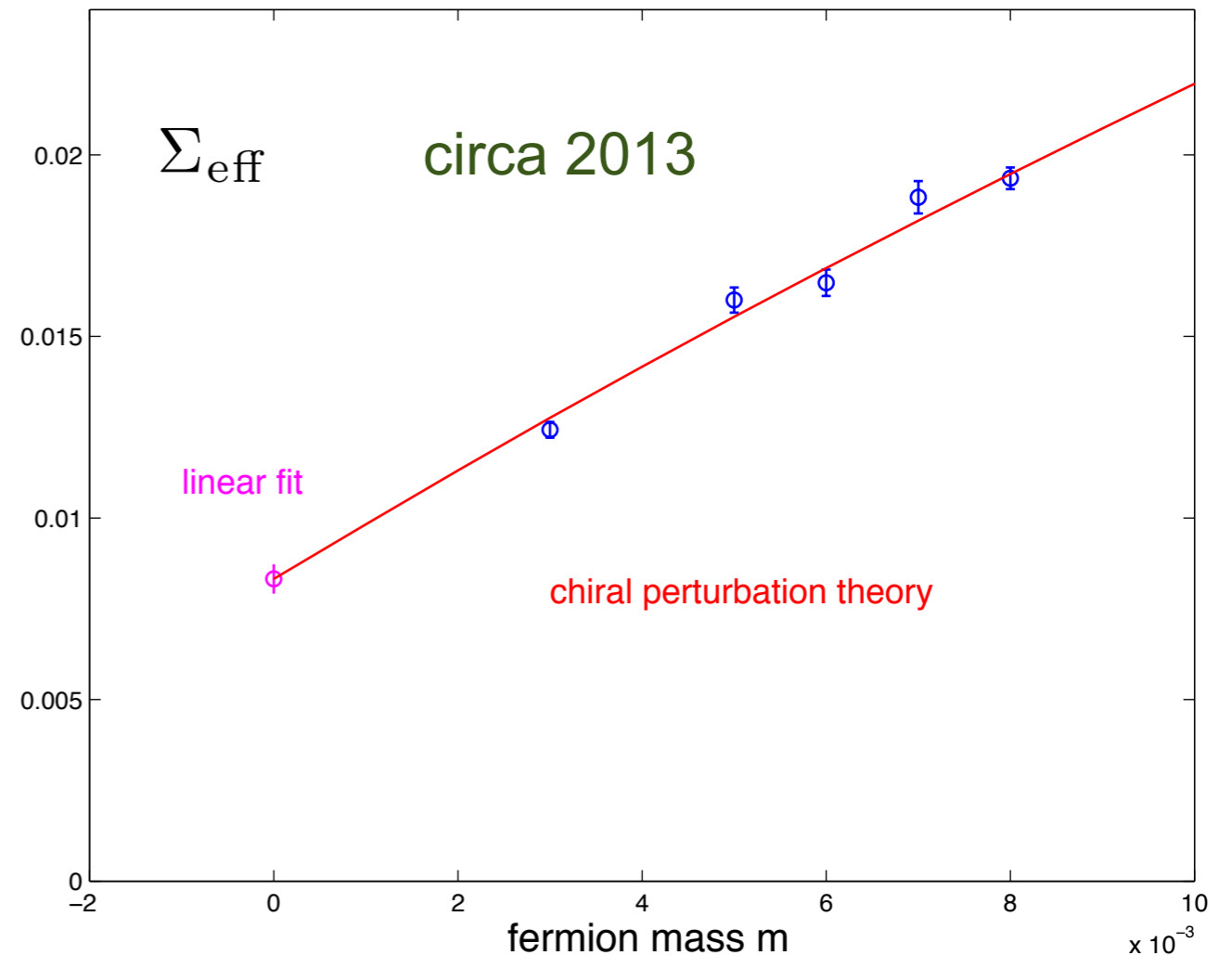
$$\frac{\Sigma_{\text{eff}}}{\Sigma} = 1 + \frac{\Sigma}{32\pi^3 N_F F^4}\left[2N_F^2|\Lambda|\arctan\frac{|\Lambda|}{m} - 4\pi|\Lambda| - N_F^2 m\log\frac{\Lambda^2 + m^2}{\mu^2} - 4m\log\frac{|\Lambda|}{\mu}\right]$$

- new stochastic method allows the extension of chiPT analysis and study topology
- m and the scale on the spectrum can be tuned more freely in partial quenching

The chiral condensate in the sextet theory

analyzis of Dirac spectrum

building correlators

insight into $\sqrt{}$

Dirac spectrum on original gauge configurations

β=3.20 $32^3 \times$ 64   m=0.003

Quartets of Q=−1 Dirac spectrum on gradient flow

β=3.20 $32^3 \times$ 64 m=0.003

t=3 on gradient flow

Dirac spectrum shows degenerate quartets
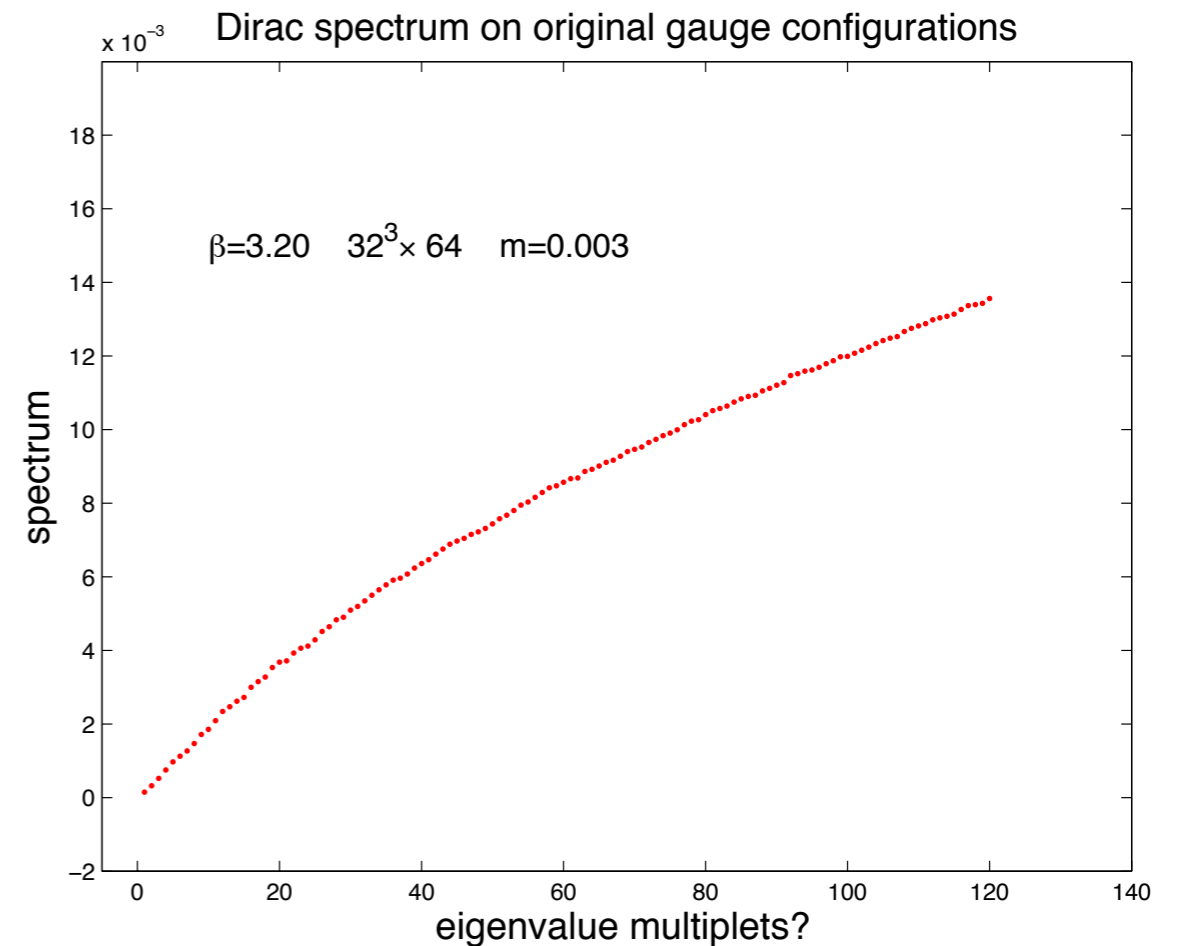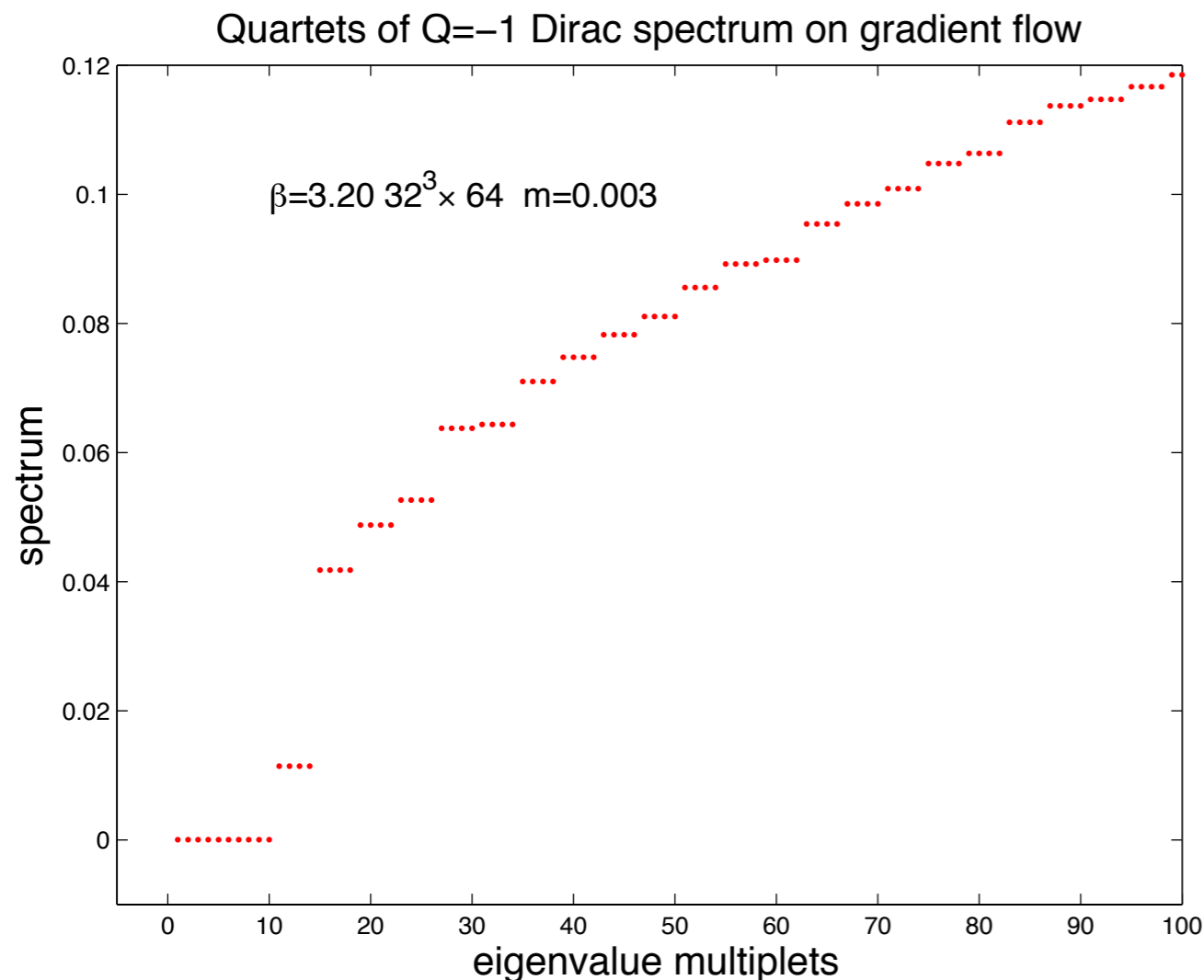
index theorem is perfect

10*Q zero modes in sextet $D^{\dagger}D$ op

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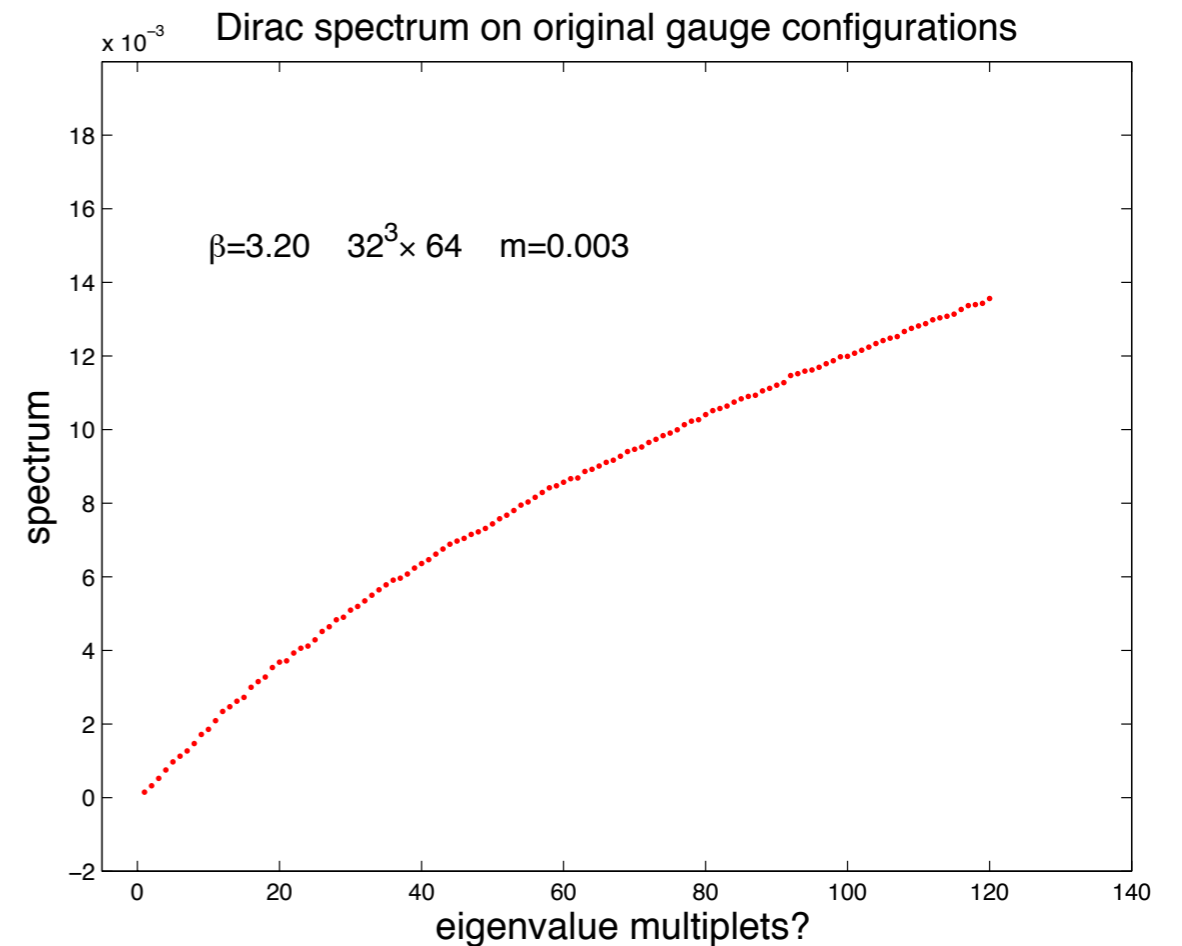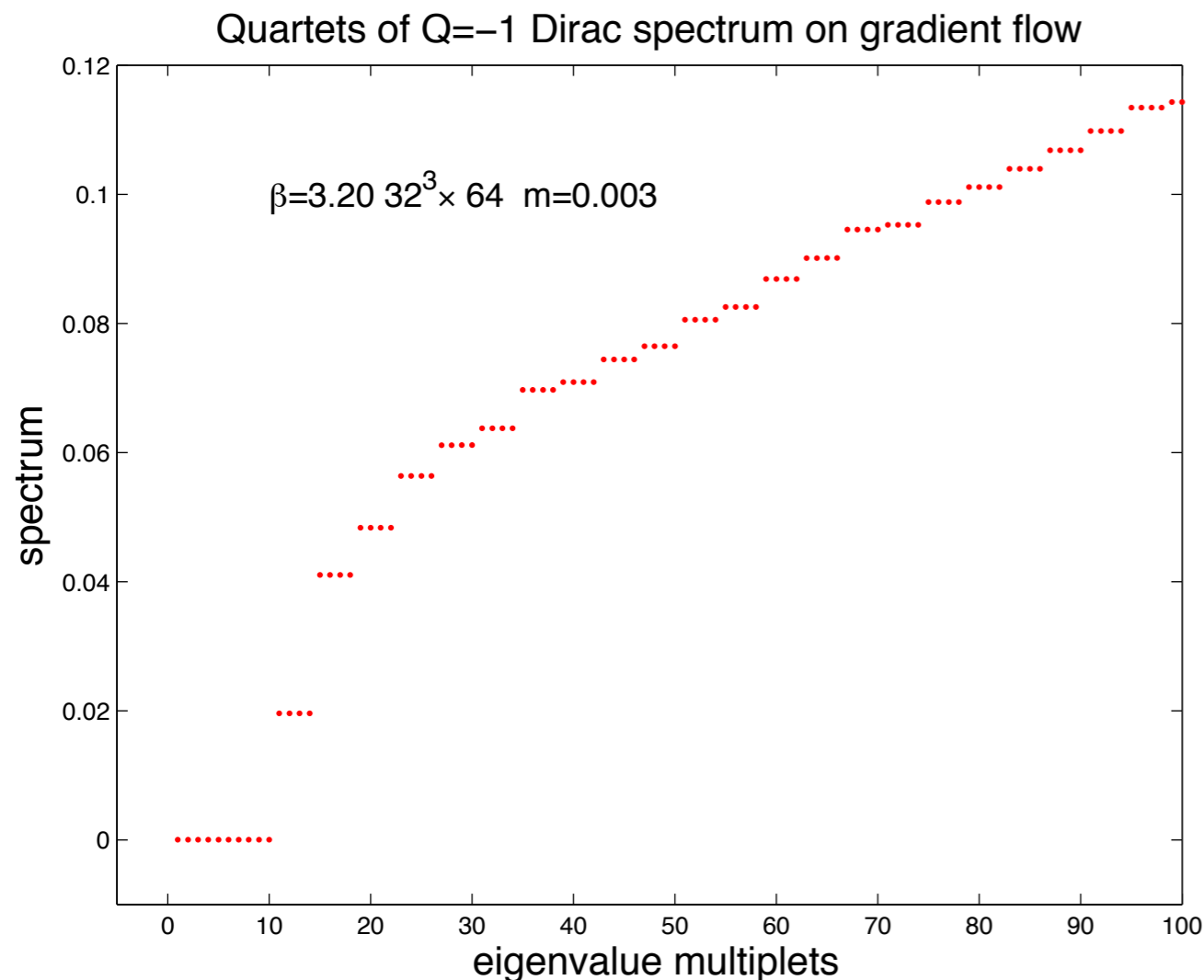
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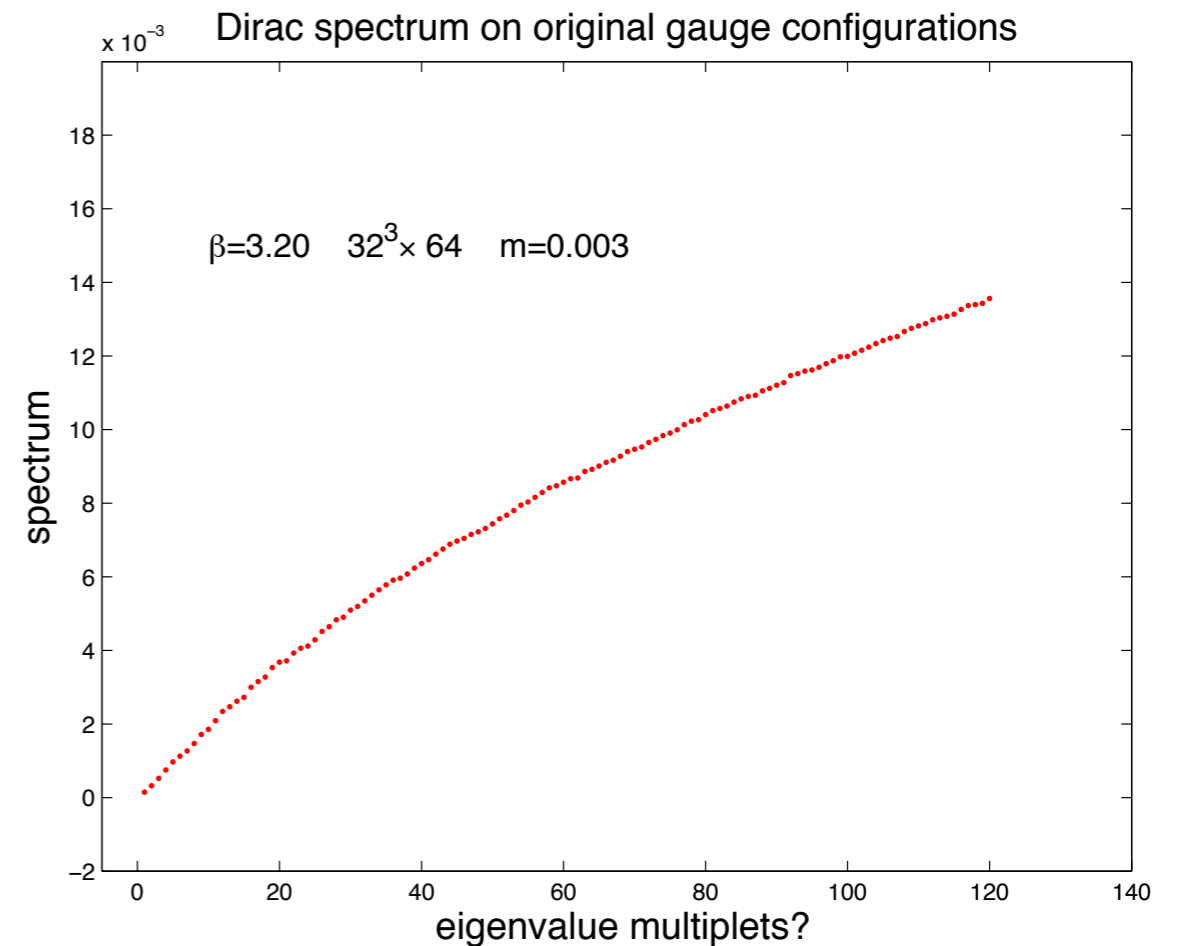
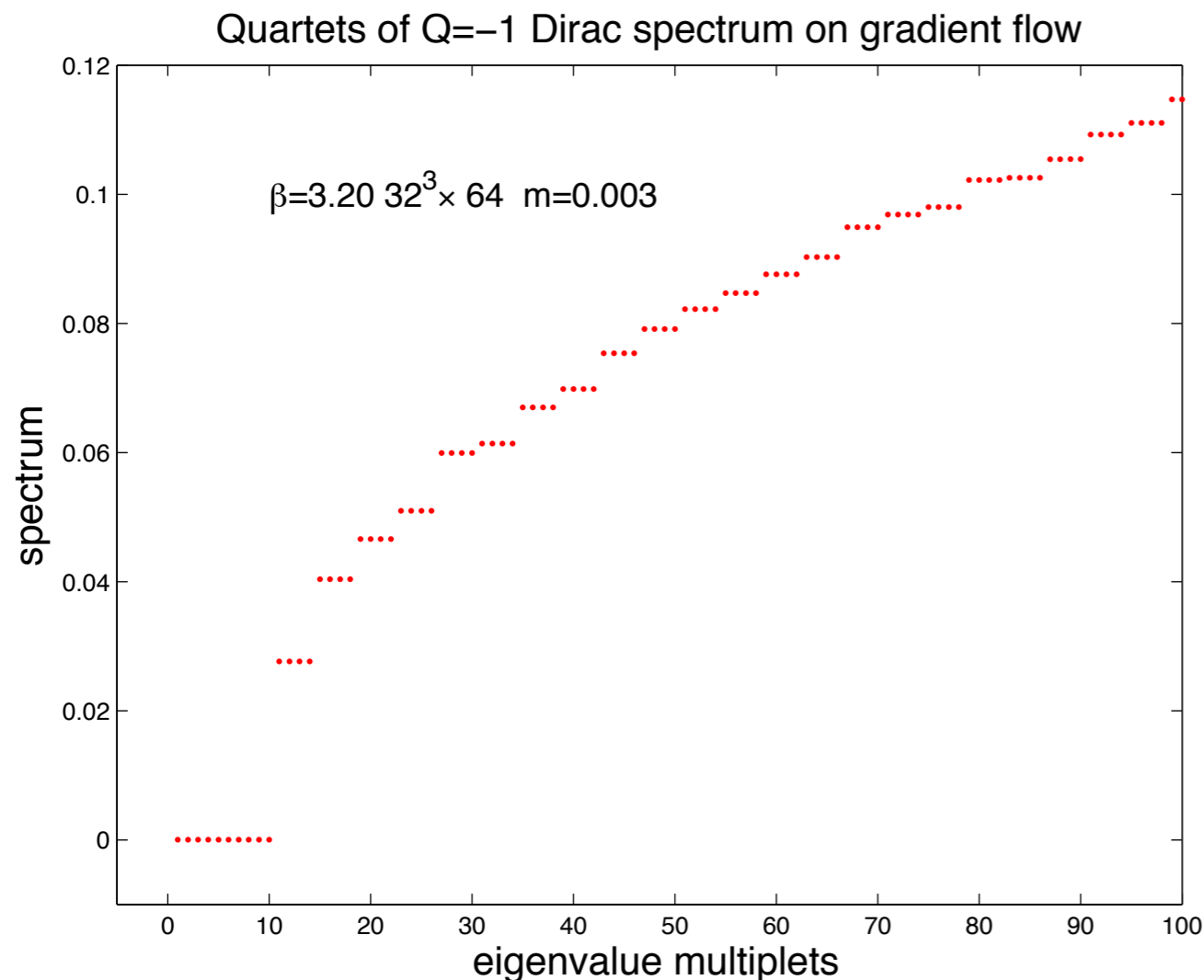index theorem is perfect

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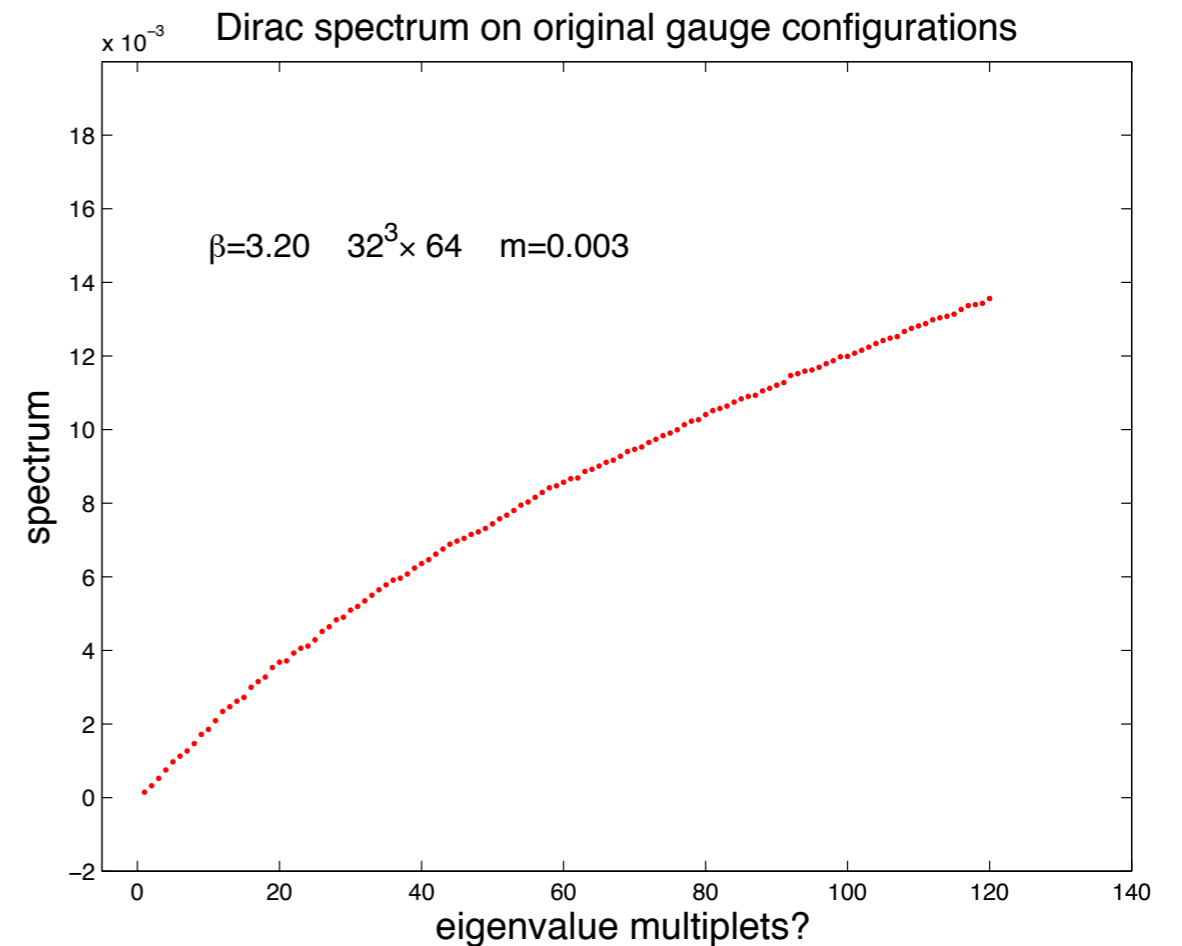
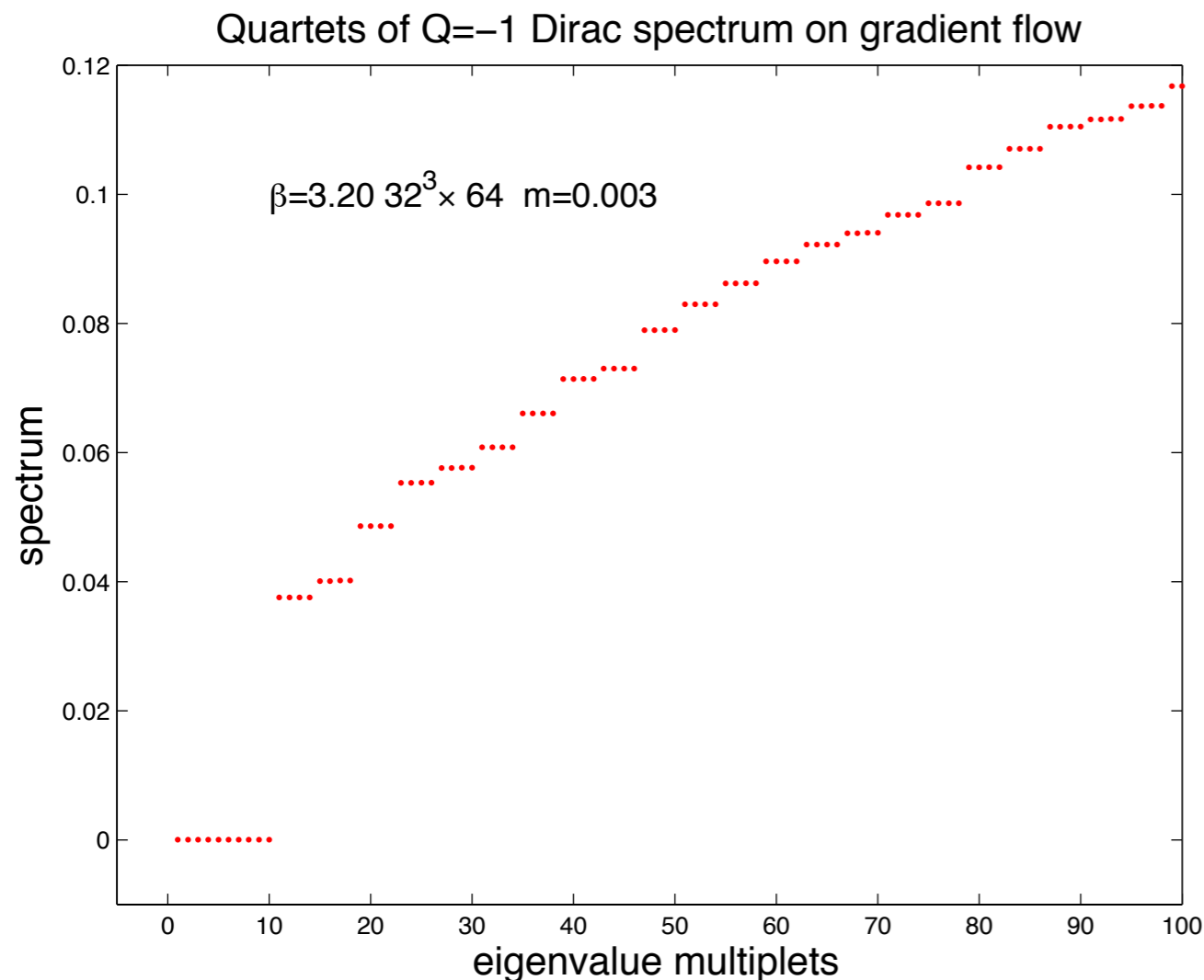index theorem is perfect

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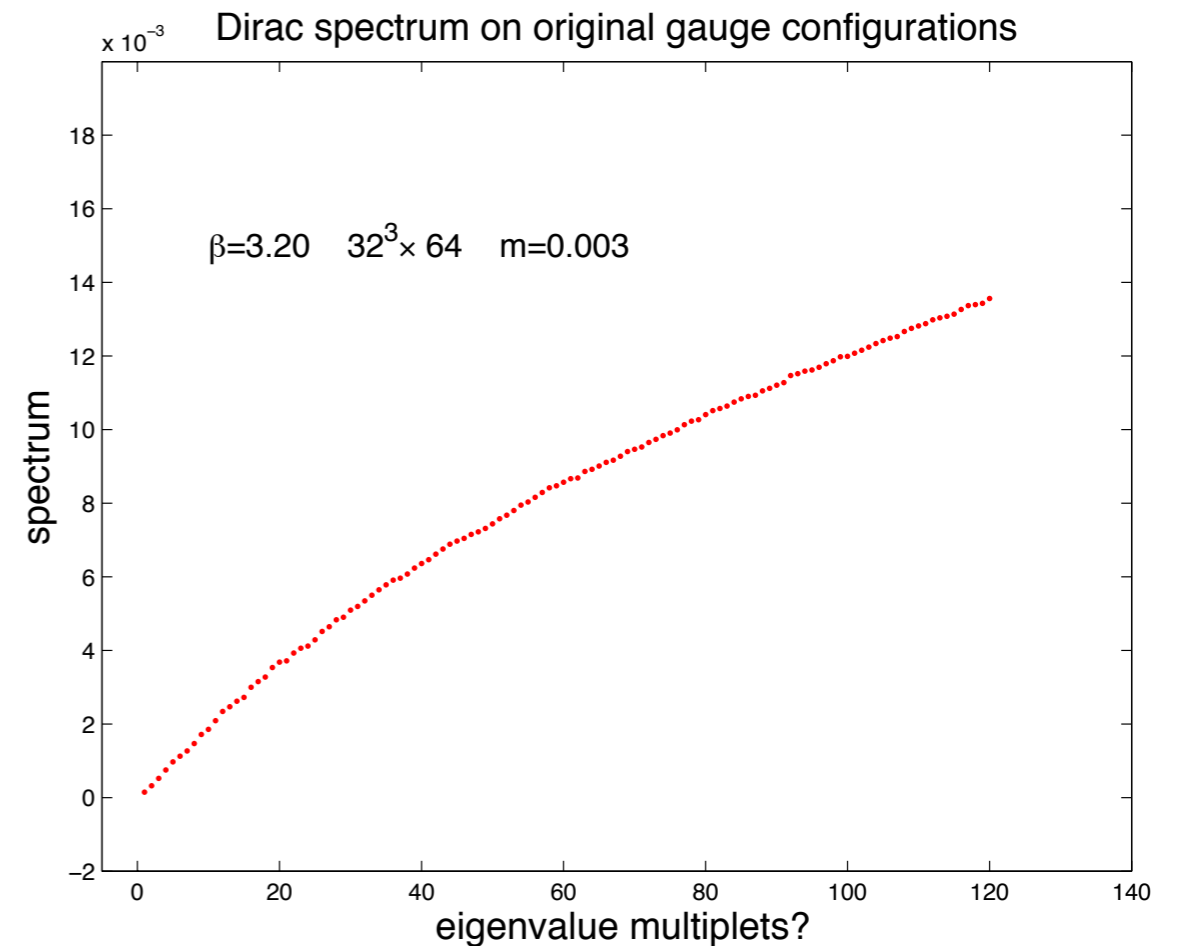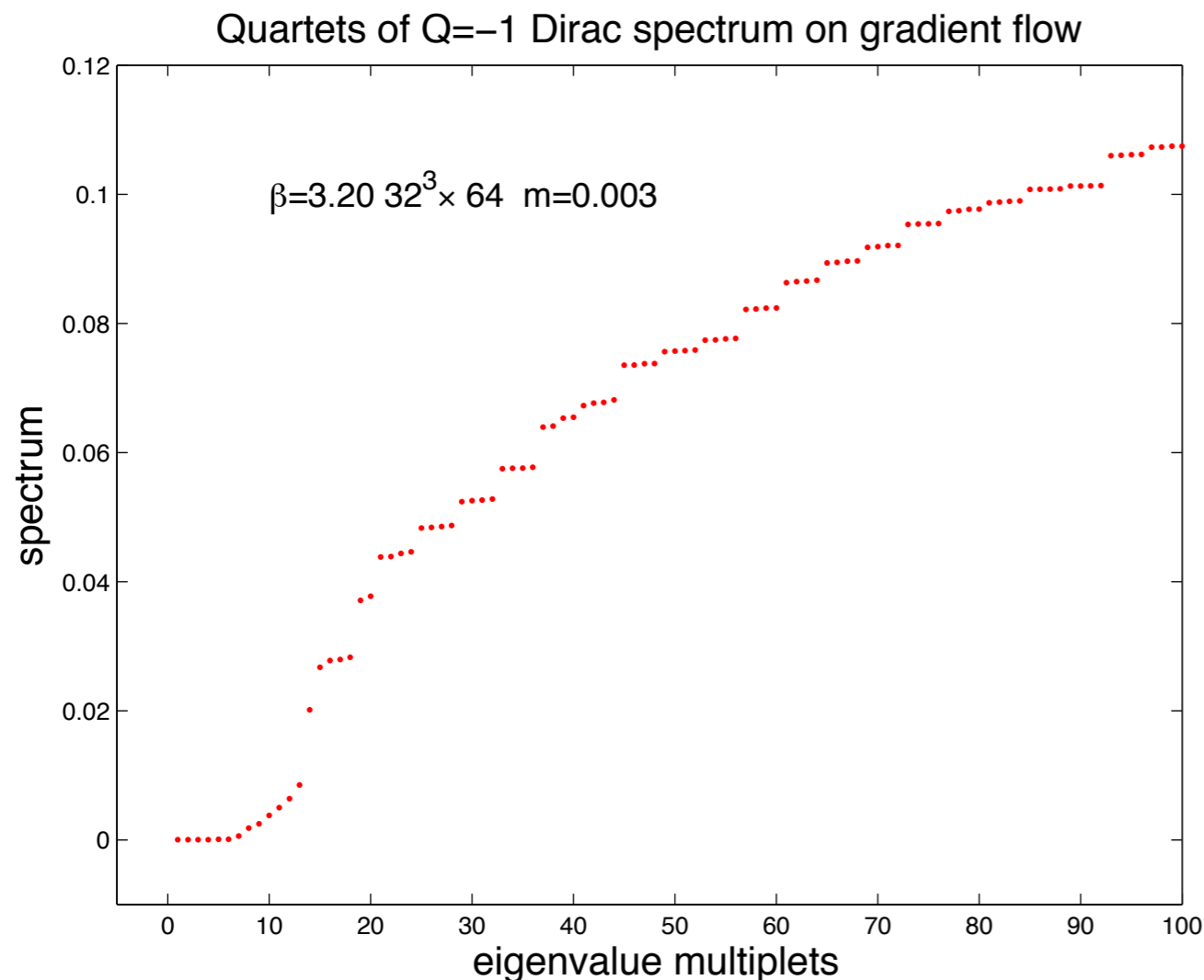index theorem is perfect

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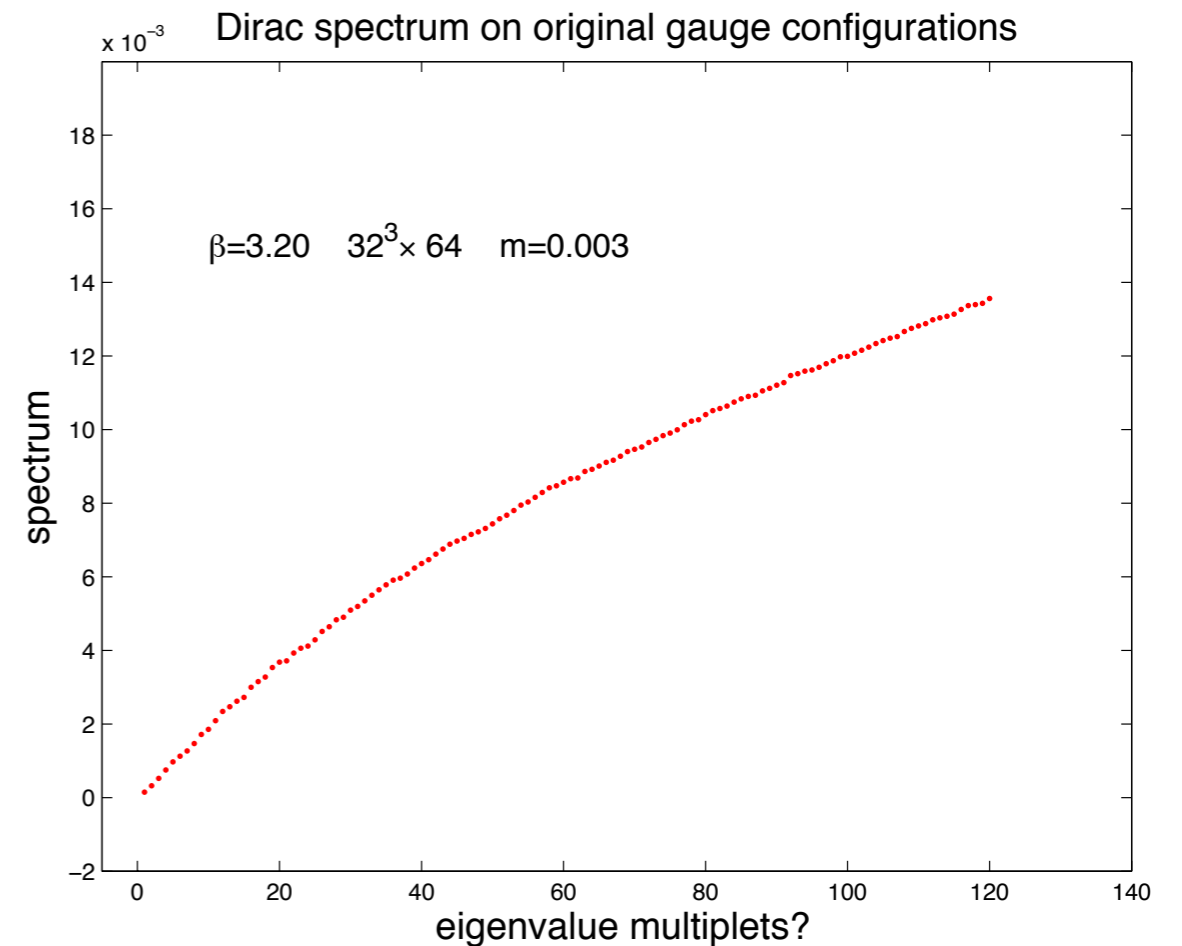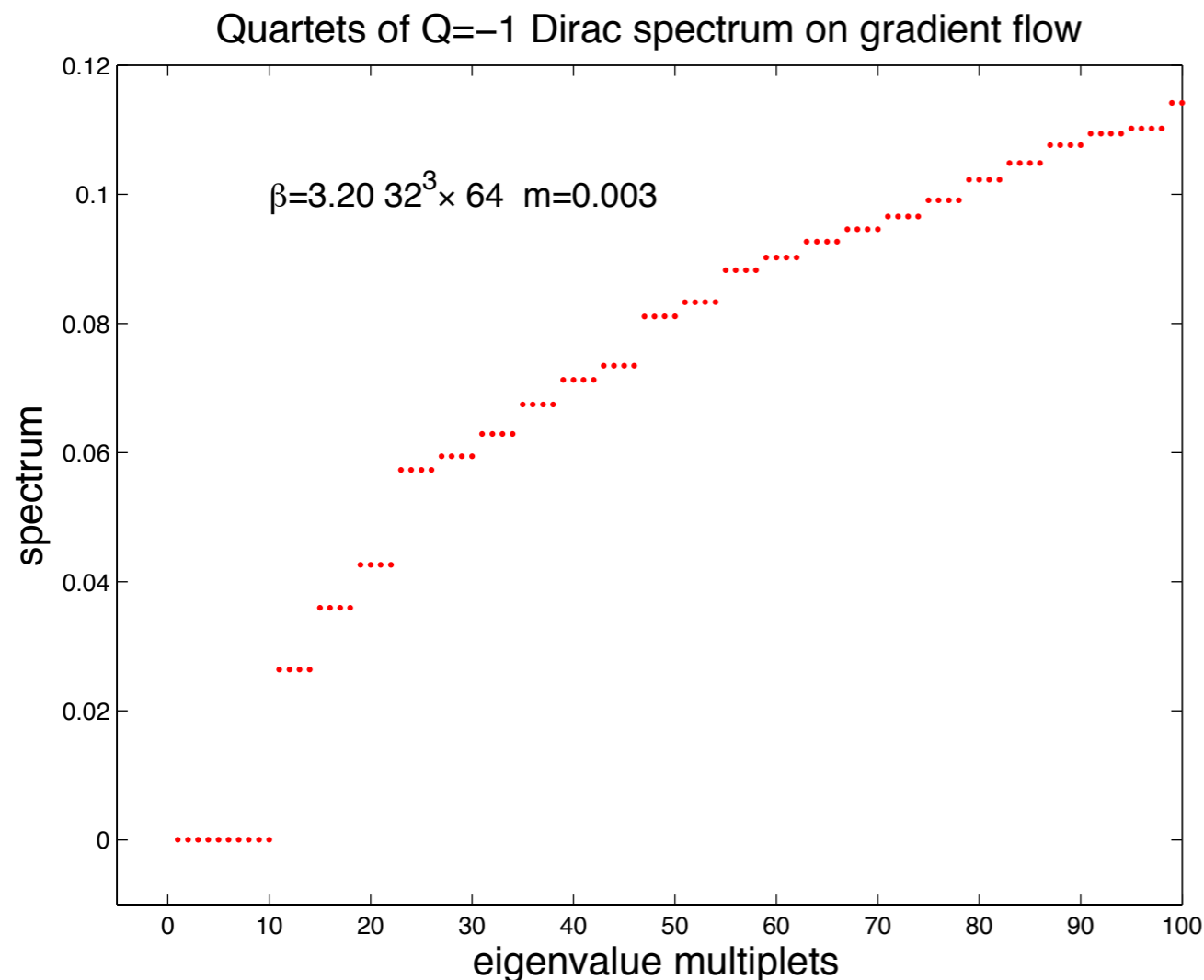index theorem is perfect

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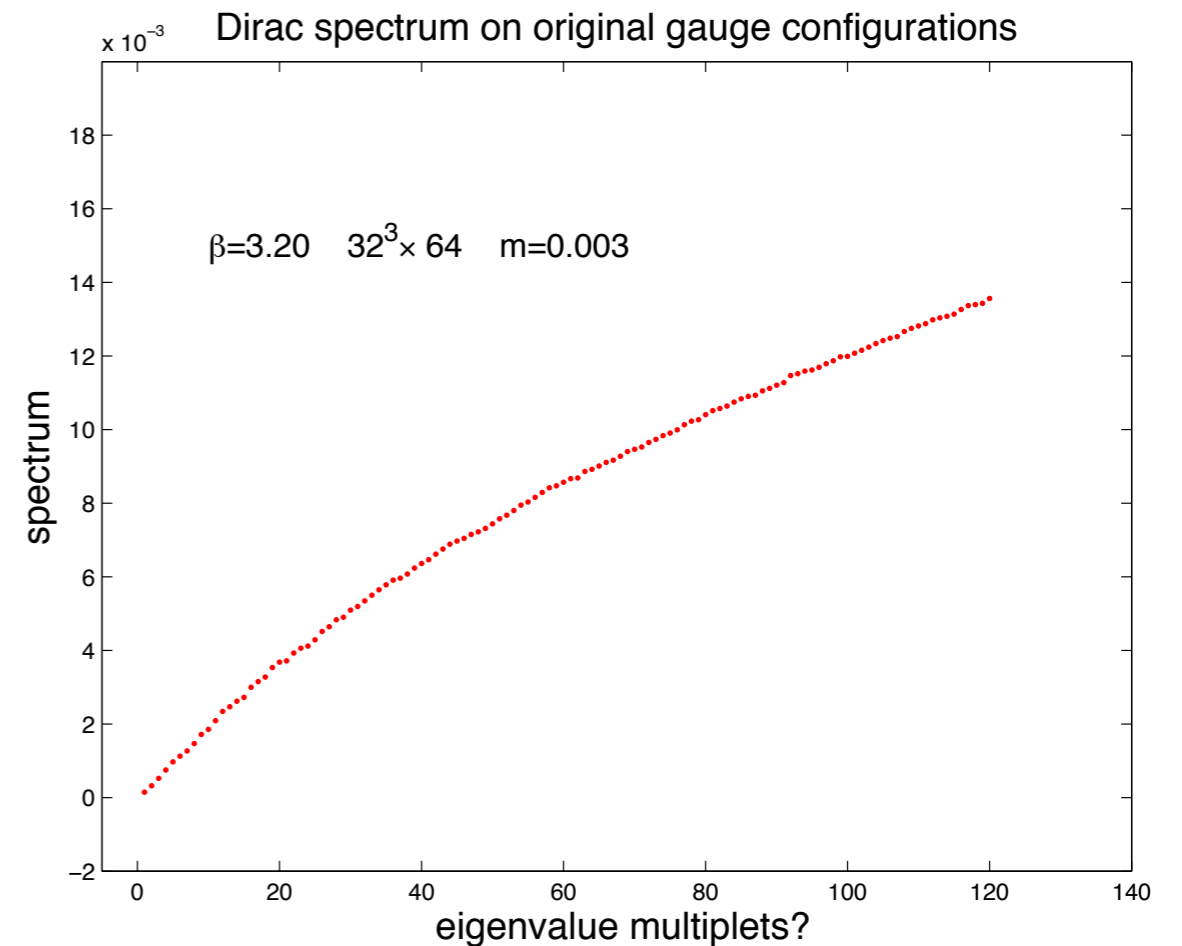index theorem is perfect

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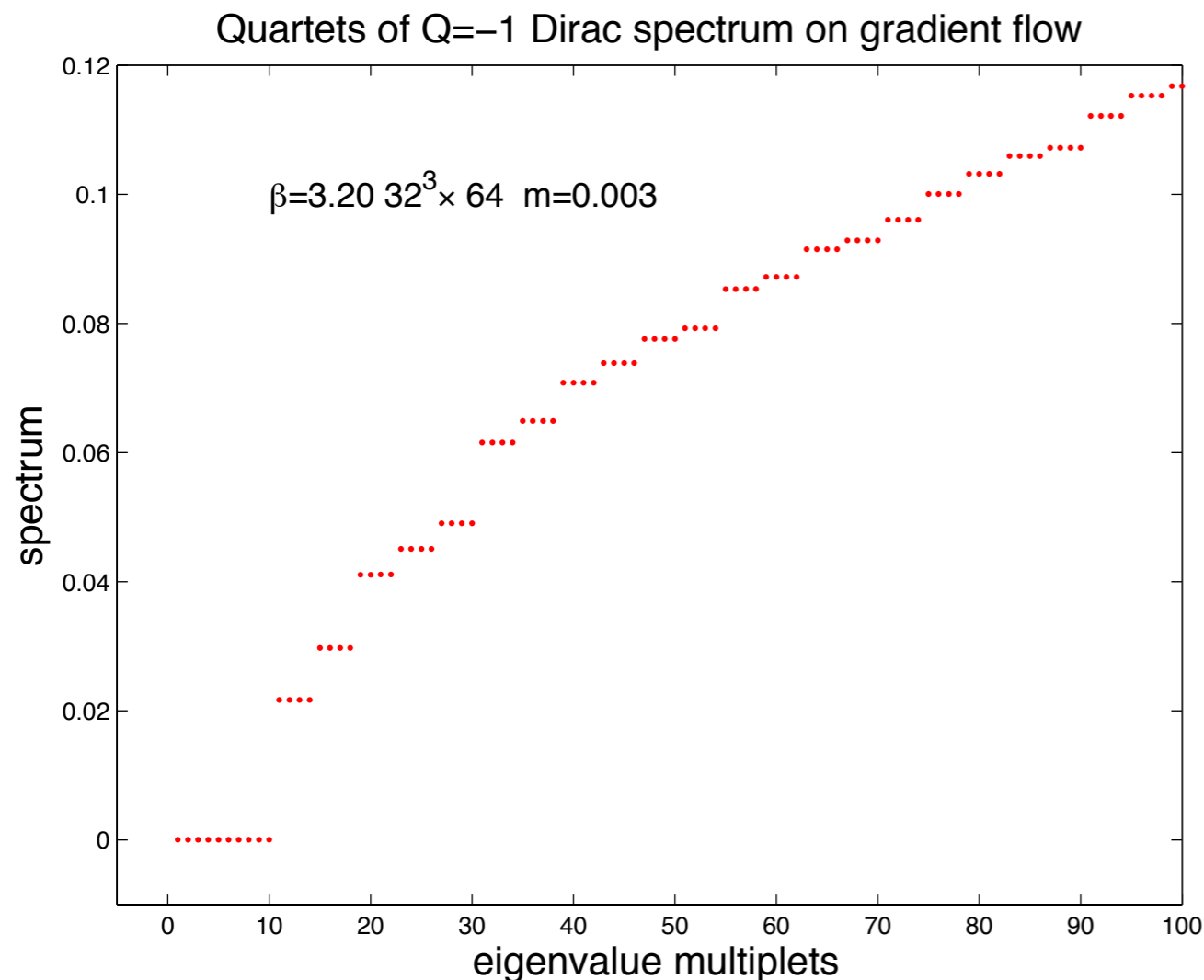
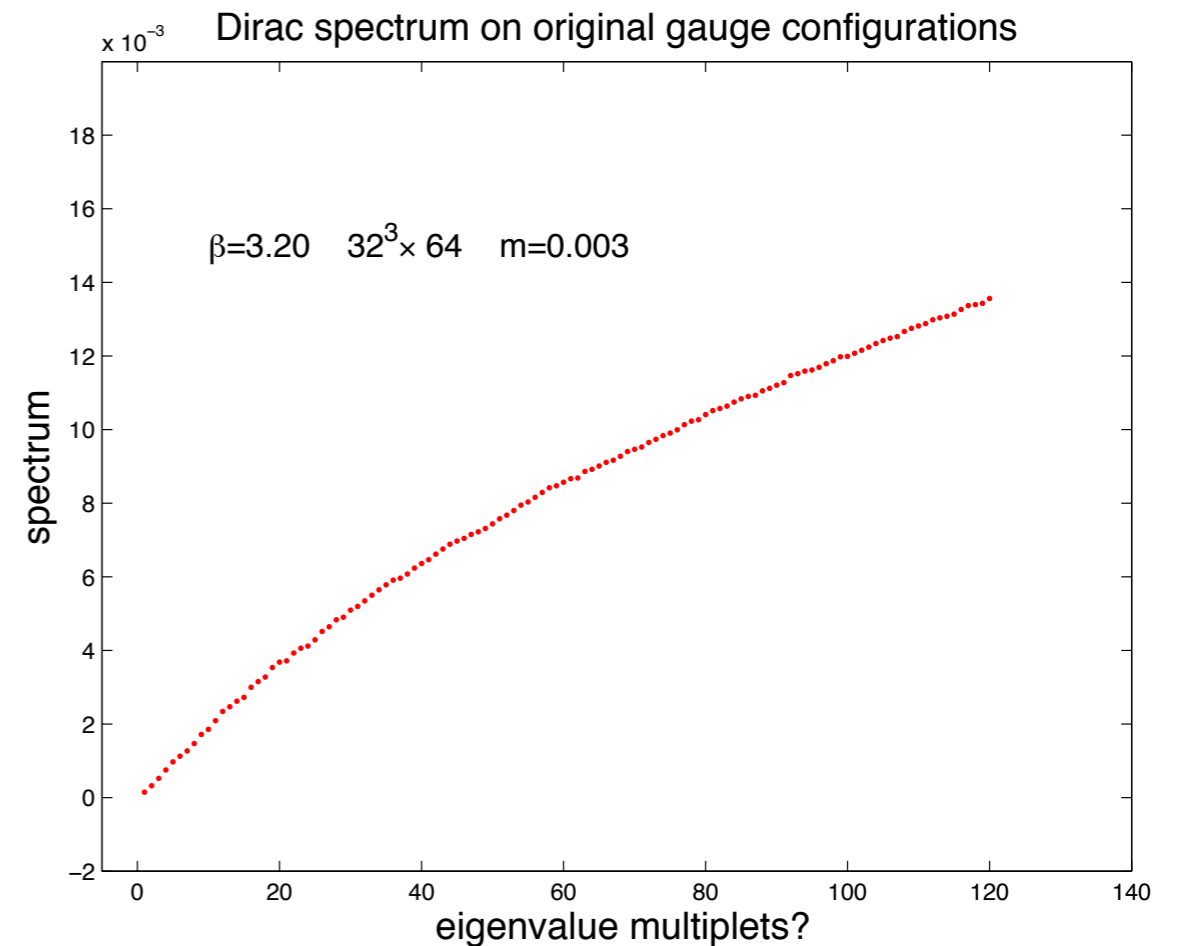index theorem is perfect

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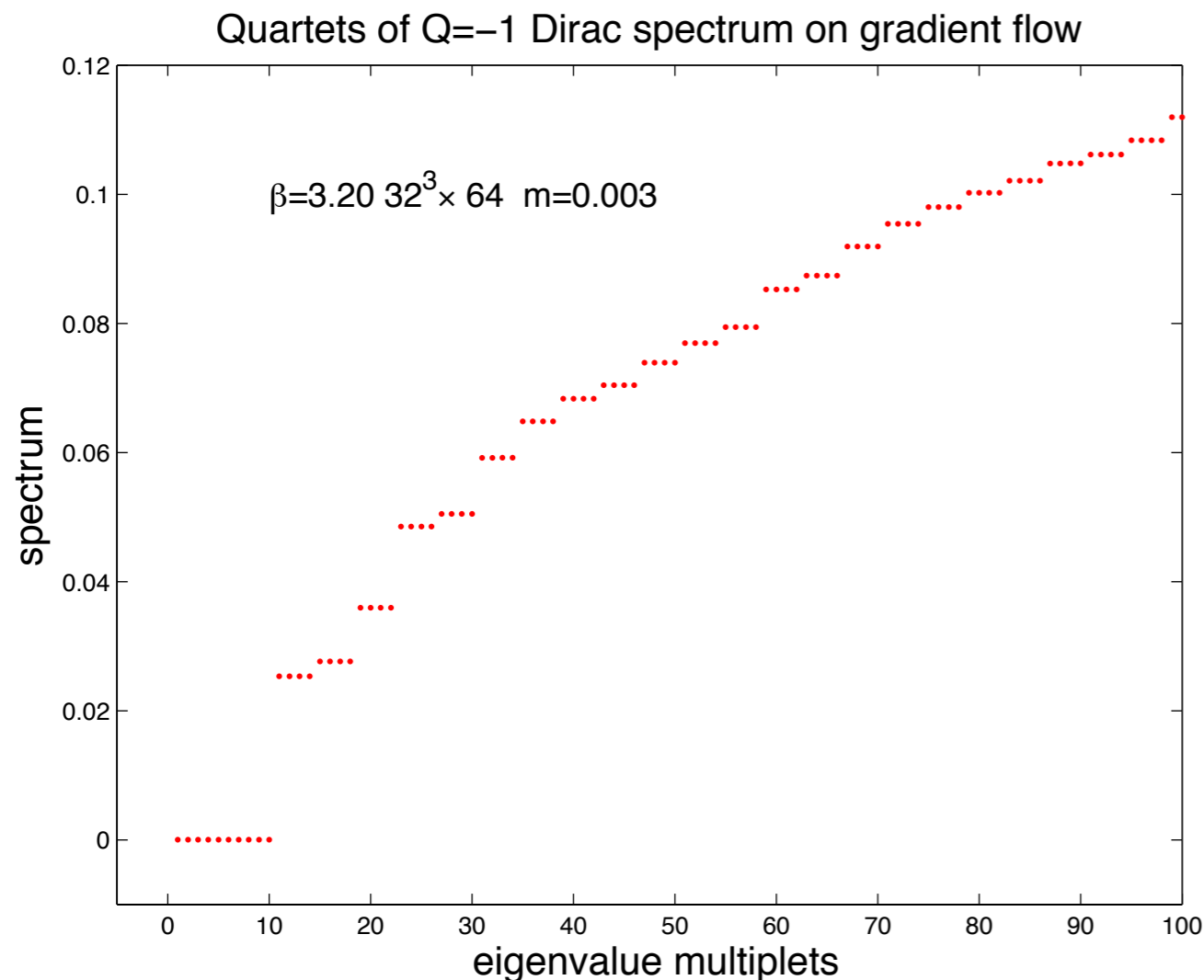
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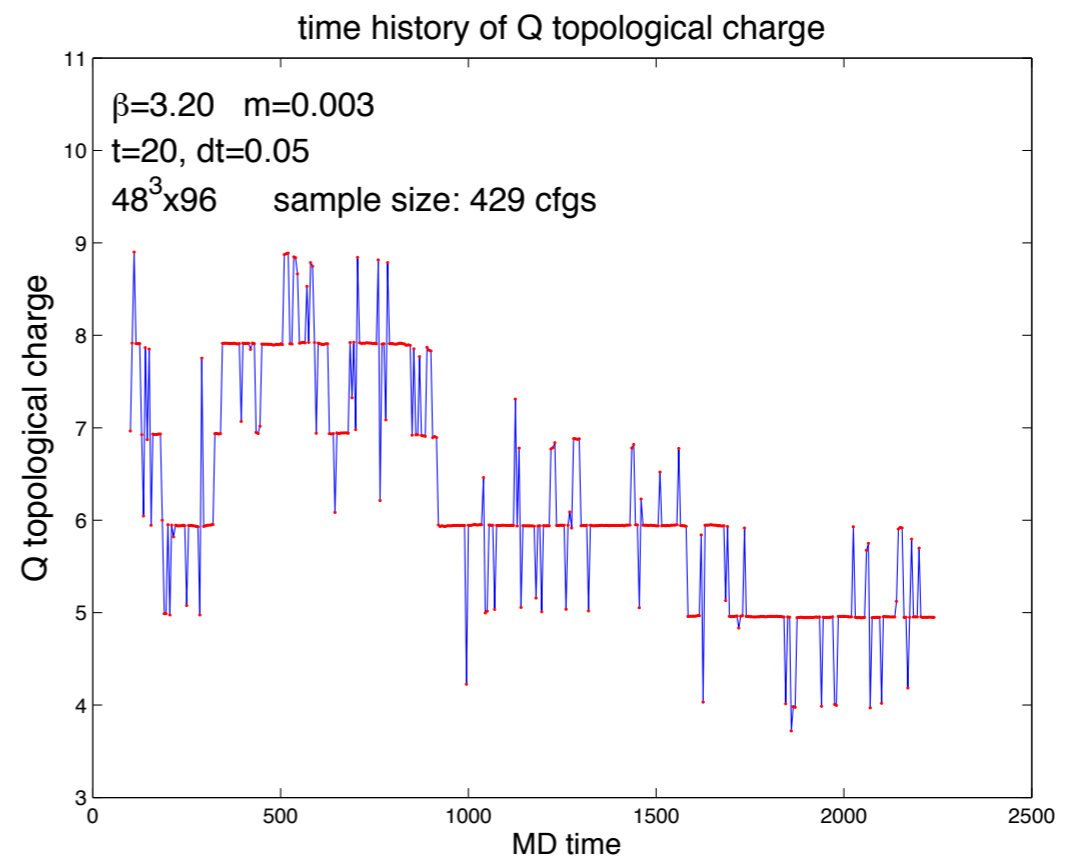Dirac spectrum on original gauge configurations
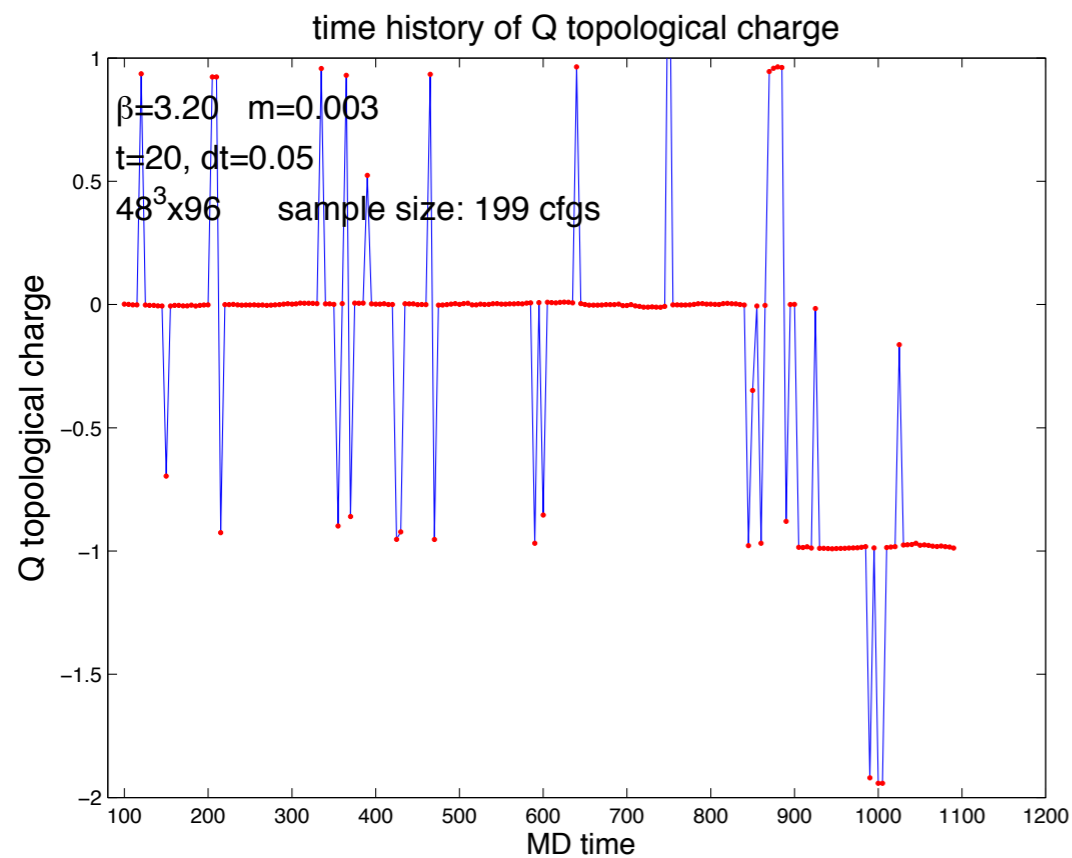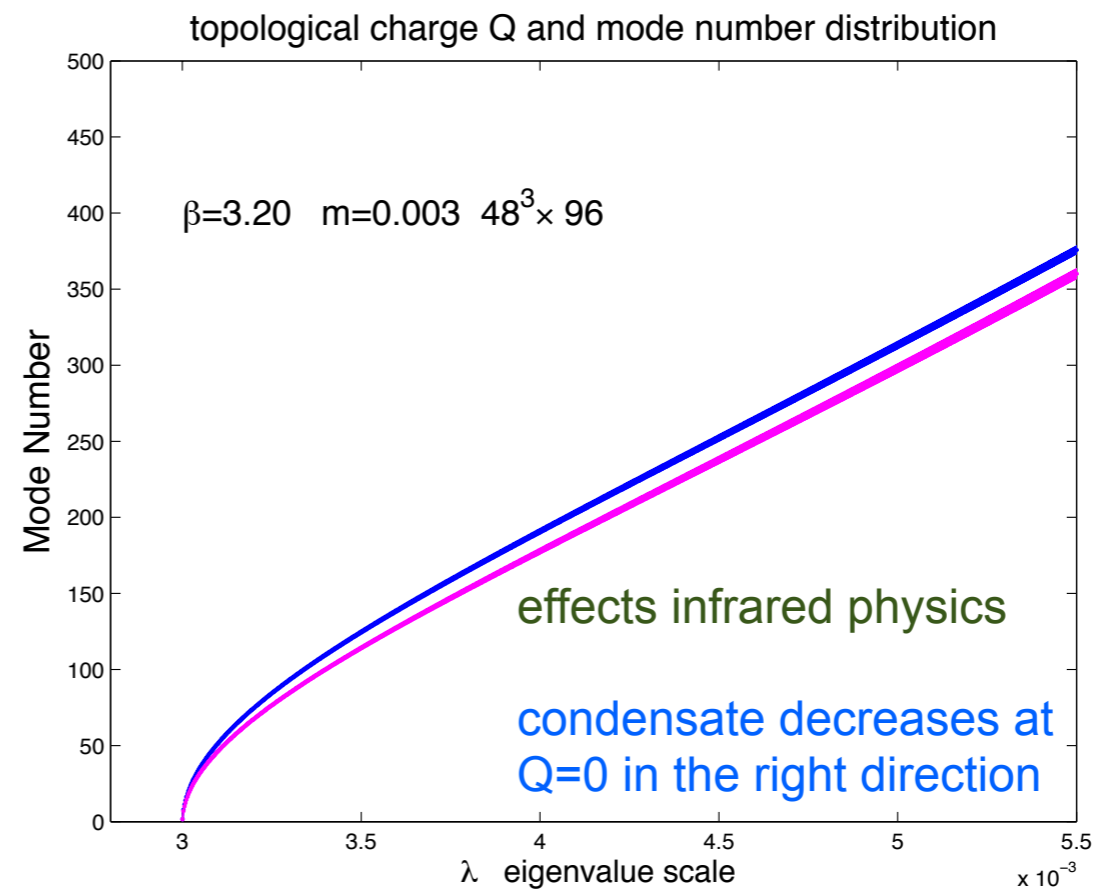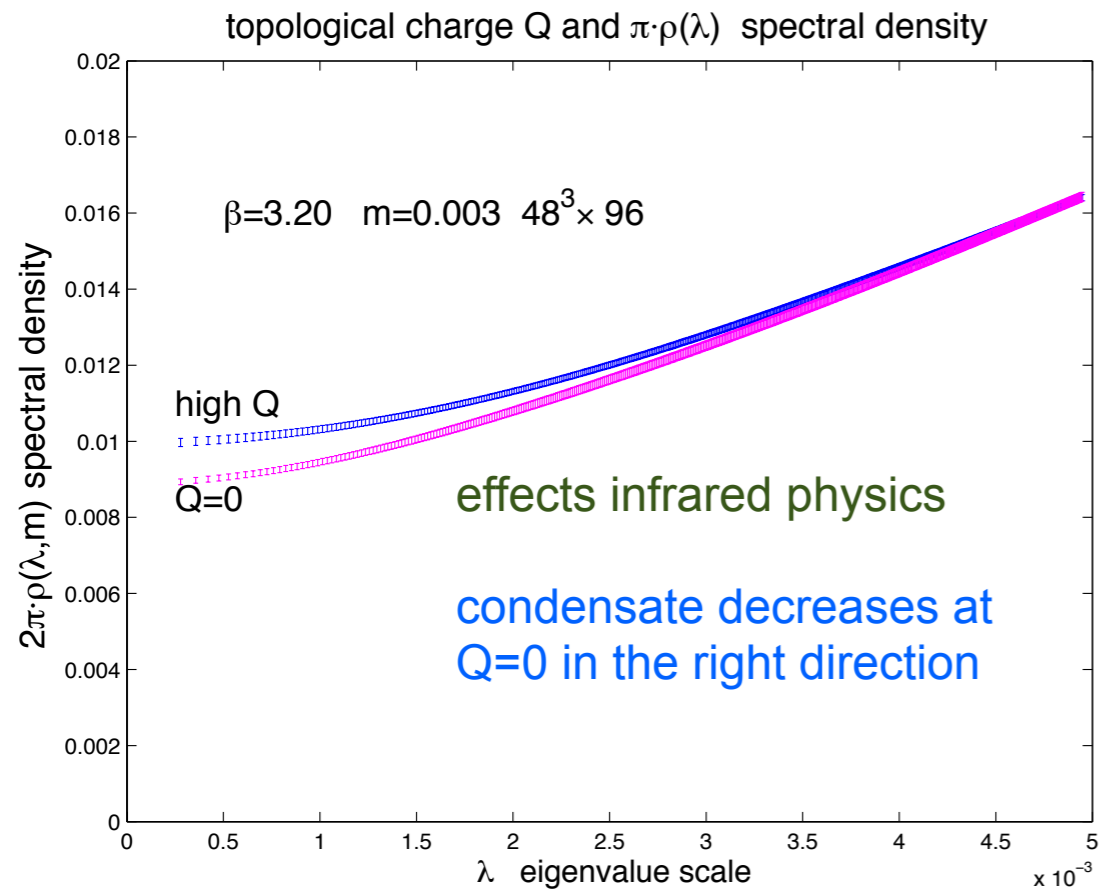
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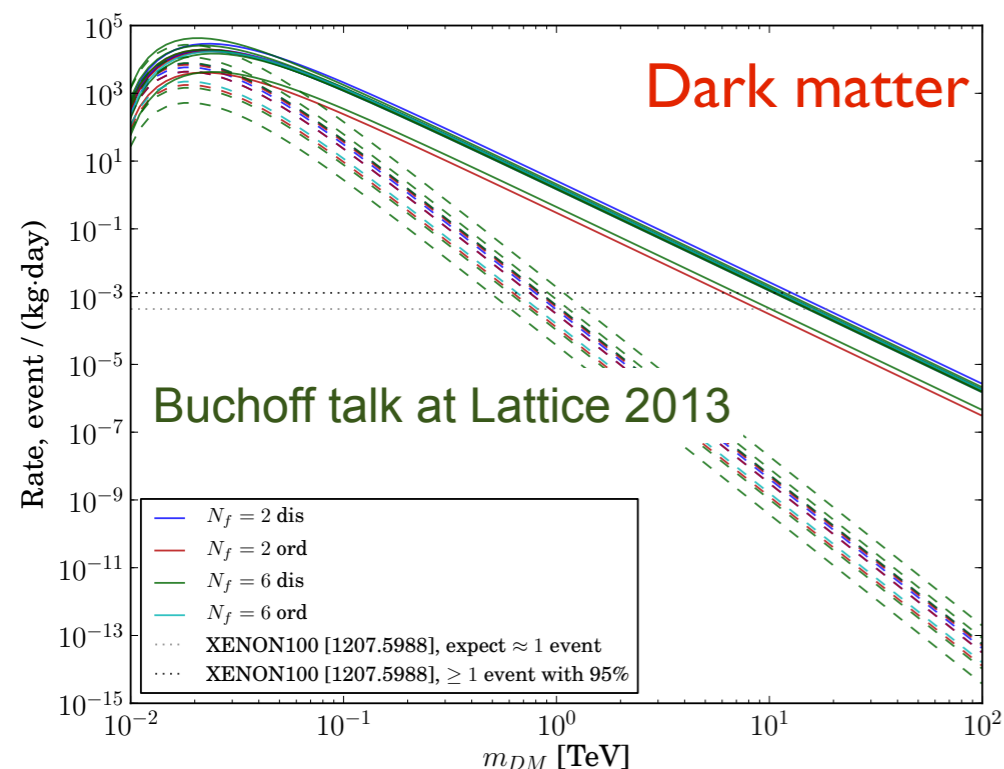# The chiral condensate in the sextet theory

Early universe

Kogut-Sinclair work finite temperature χSB phase transition?
Relevance in early cosmology (order of the phase transition?)

The Total Energy of the Universe:

Dark matter

self-interacting?
O(barn) cross section would be challenging

Vacuum Energy (Dark Energy) ∼ 67 %
Dark Matter ∼ 29 %
Visible Baryonic Matter ∼ 4 %

Dark matter

Buchoff talk at Lattice 2013

Legend:
- $N_f = 2$ dis
- $N_f = 2$ ord
- $N_f = 6$ dis
- $N_f = 6$ ord
- XENON100 [1207.5988], expect ≈ 1 event
- XENON100 [1207.5988], ≥ 1 event with 95%

Axis labels: Rate, event / (kg·day) vs m_{DM} [TeV]

- lattice BSM phenomenology of dark matter
  pioneering LSD work

- Nf=2   Qu=2/3 Qd = -1/3
  udd neutral dark matter candidate

- dark matter candidate sextet Nf=2
  electroweak active in the application

- there is room for third heavy fermion
  flavor as electroweak singlet

- rather subtle sextet baryon
  construction (symmetric in color)   Mondal 8C Friday

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Summary and Outlook

Simplest composite scalar is light near conformality ?

light scalar (dilaton-like?) emerging   close to conformal window?

running (walking) coupling in progress   difficult, Gradient Flow is huge improvement

chiral condensate   new method is very promising

spectroscopy   emerging resonance spectrum ~ 2-3 TeV

dark matter   implications are intriguing
strong self-interactions?

Tuning with third flavor ?

We have a candidate for minimal Higgs impostor to make it fail !

Our job is not to oversell, but do everything we can to kill the model !

If we fail to kill, the model will speak for itself without naming rights