The chiral condensate from the Dirac spectrum in BSM gauge theories

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work with Julius Kuti, Zoltan Fodor, Daniel Nogradi, Chik Him Wong

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which theory and why

$SU(3)$ gauge theory $N_F = 2$ flavors, two-index symmetric representation

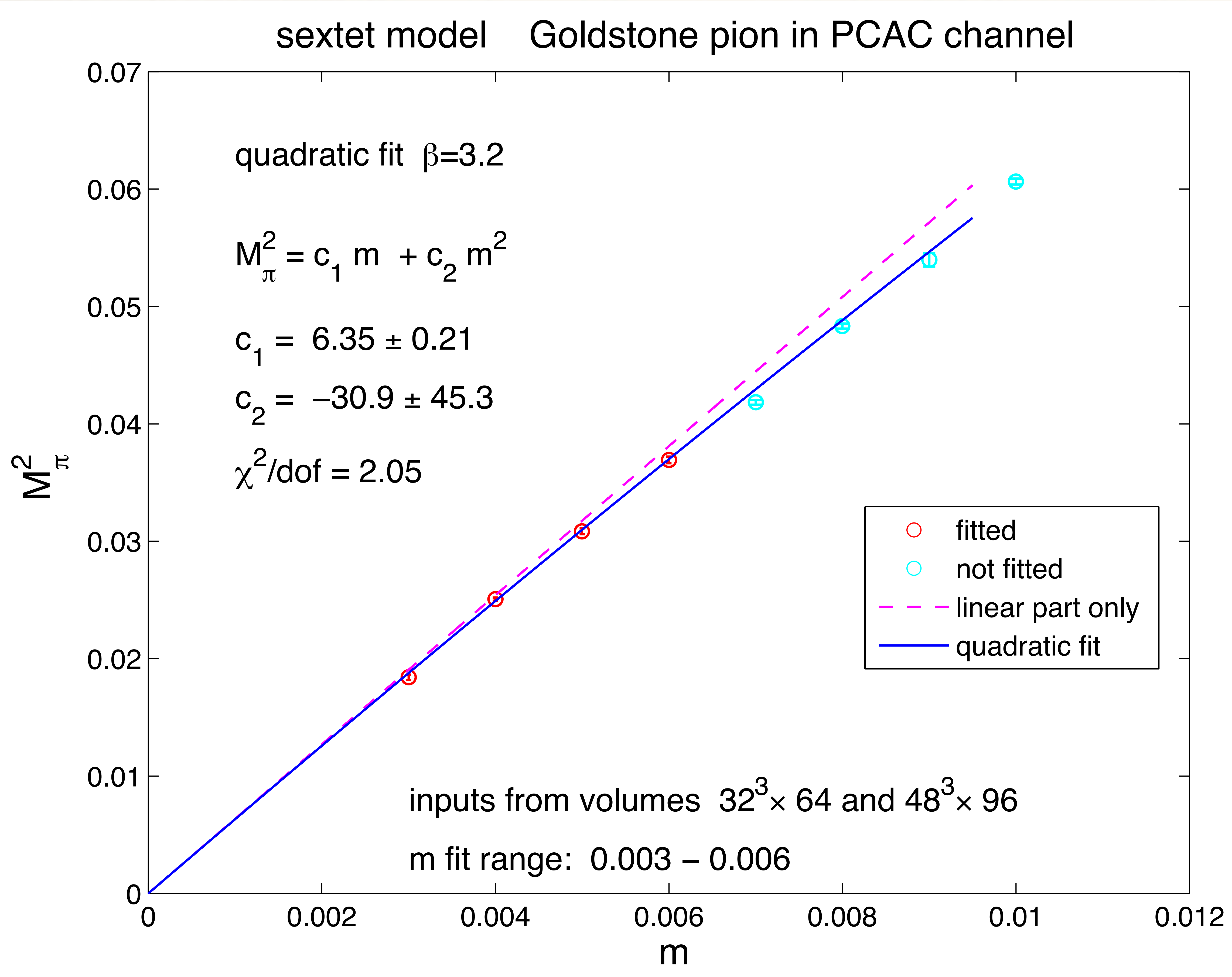
shorthand: sextet NMWT (next to minimal walking technicolor) SU(3)-MWT

why?

- if chiralSB occurs, generates 3 Goldstones - exact match to EW gauge bosons
- unusual representation, possible near conformal behavior for small N_F
- possible dark matter, no Witten anomaly
- our previous work suggests chiralSB *does* occur 1209.0391
- new result: light composite scalar Higgs impostor Ricky Wong Mon 6:30

other work: Sinclair, Kogut; DeGrand, Shamir, Svetitsky

Goldstone bosons



tree-level Symanzik improved gauge

stout-smeared staggered

several volumes up to 96×48^3

mass range down to $M_\pi \sim 0.13$

finite volume effect $< 1\%$

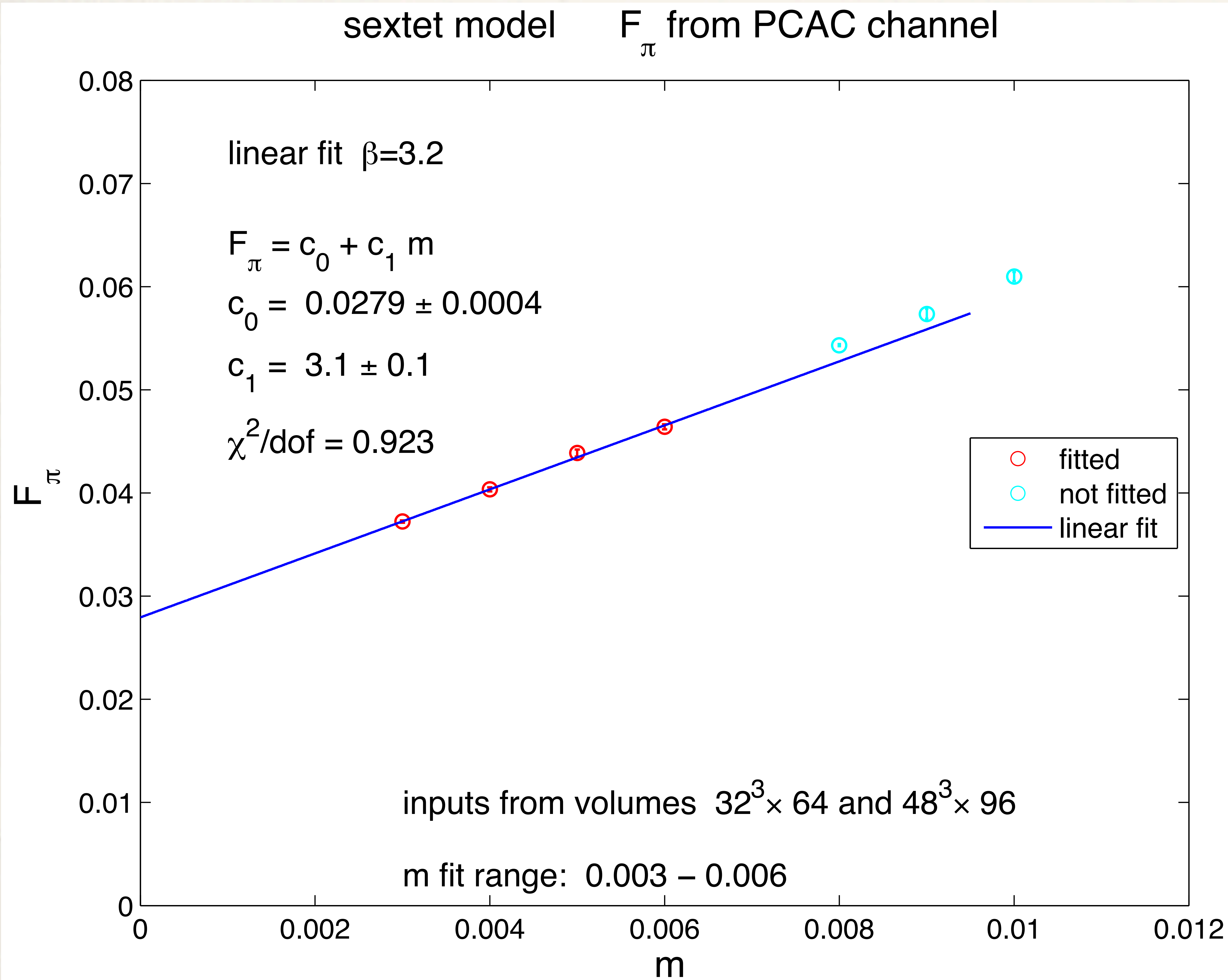
is the pion a Goldstone boson? Yes

mass-dependence matches
chiral PT behavior

small errors, but cannot probe possible chiral logarithms

blue points not fitted - outside chiPT regime

Goldstone decay constant



this context:
decay constant sets Electroweak scale

chiral limit $F = 246\ \mathrm{GeV}$

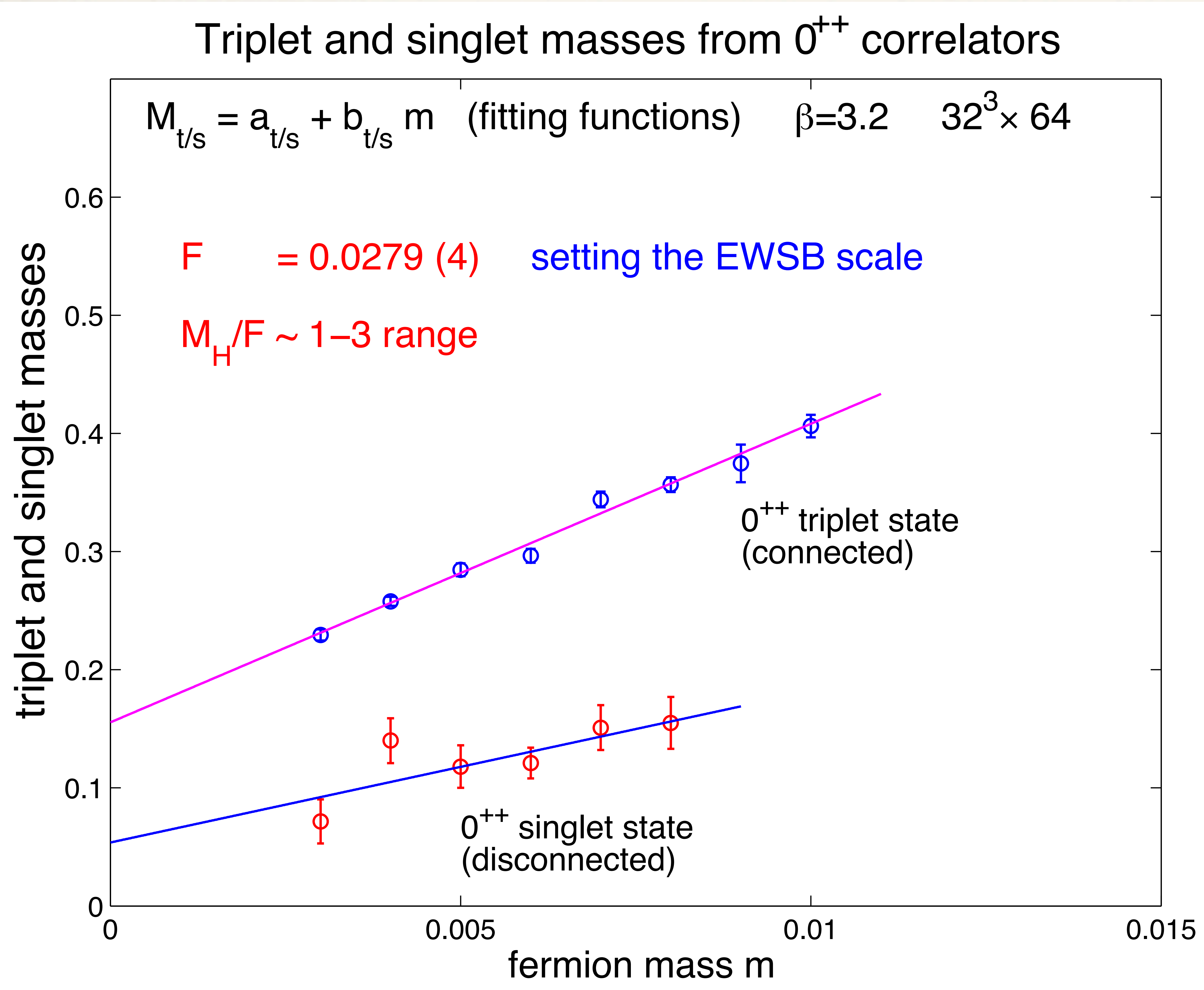
lattice volumes $L^3 \times 2L$

p-regime: want $F_\pi L > 1$
feasible for $N_F = 2$

non-zero in chiral extrapolation
(again no chiral logarithms included)

conformal hypothesis: quantities vanish as $m^{1/1+\gamma}$ Fails to describe data

light composite scalar - Higgs impostor



New Ricky Wong Mon 6:30

flavor singlet scalar measured on same ensembles

challenge: disconnected diagrams

composite scalar appears light

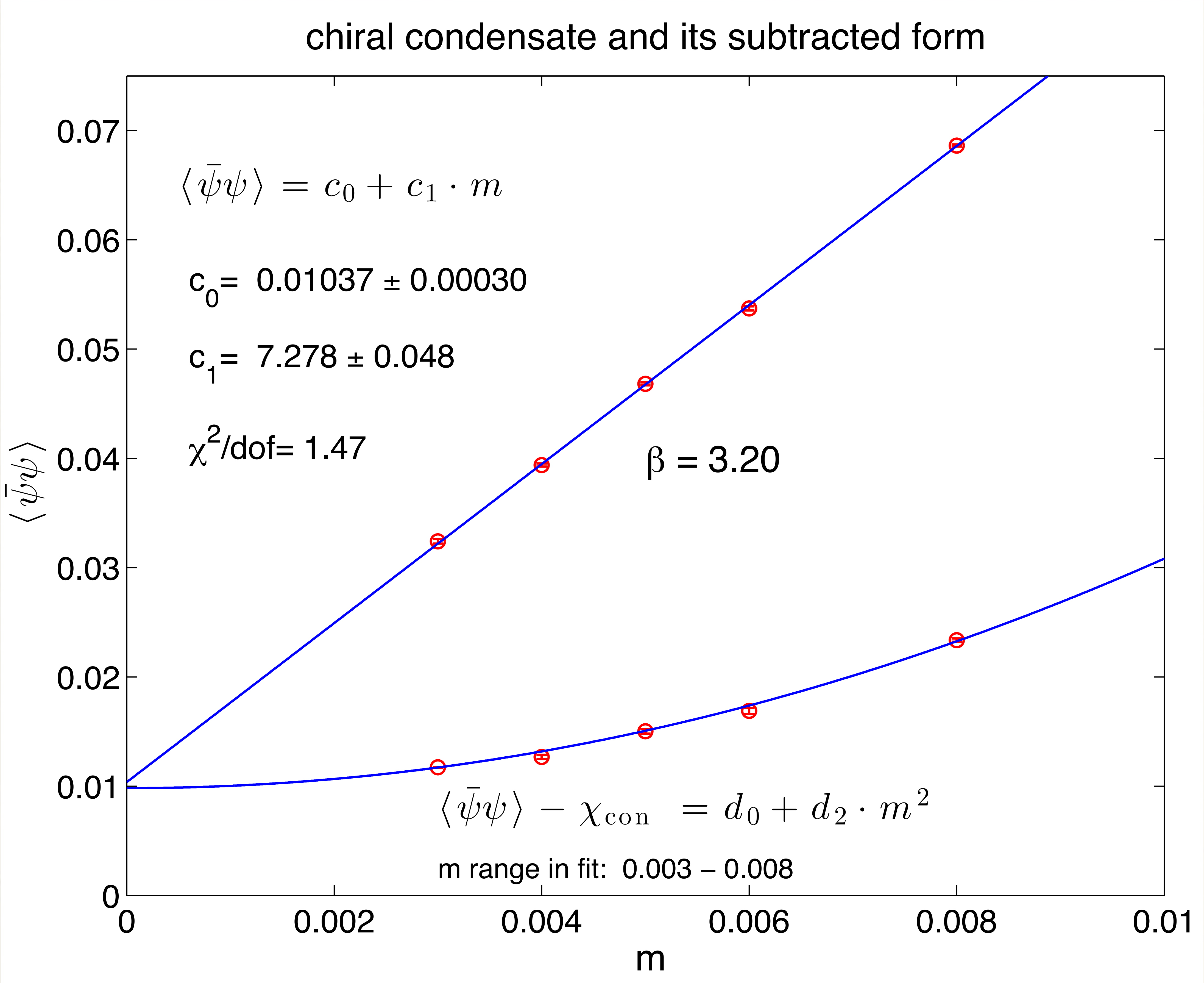
possible connection to nearby conformal window

dilaton interpretation?

the statement that strongly-interacting theories are Higgs-less looks wrong

→ crucial issue in post-Higgs discovery era

chiral condensate



direct measurement of chiral symmetry breaking via $\langle \mathrm{Tr}\ D^{-1}(m)\rangle$

steep mass dependence due to UV divergent contribution

even with small errors, chiral extrapolation is challenging

improvement: independent observable

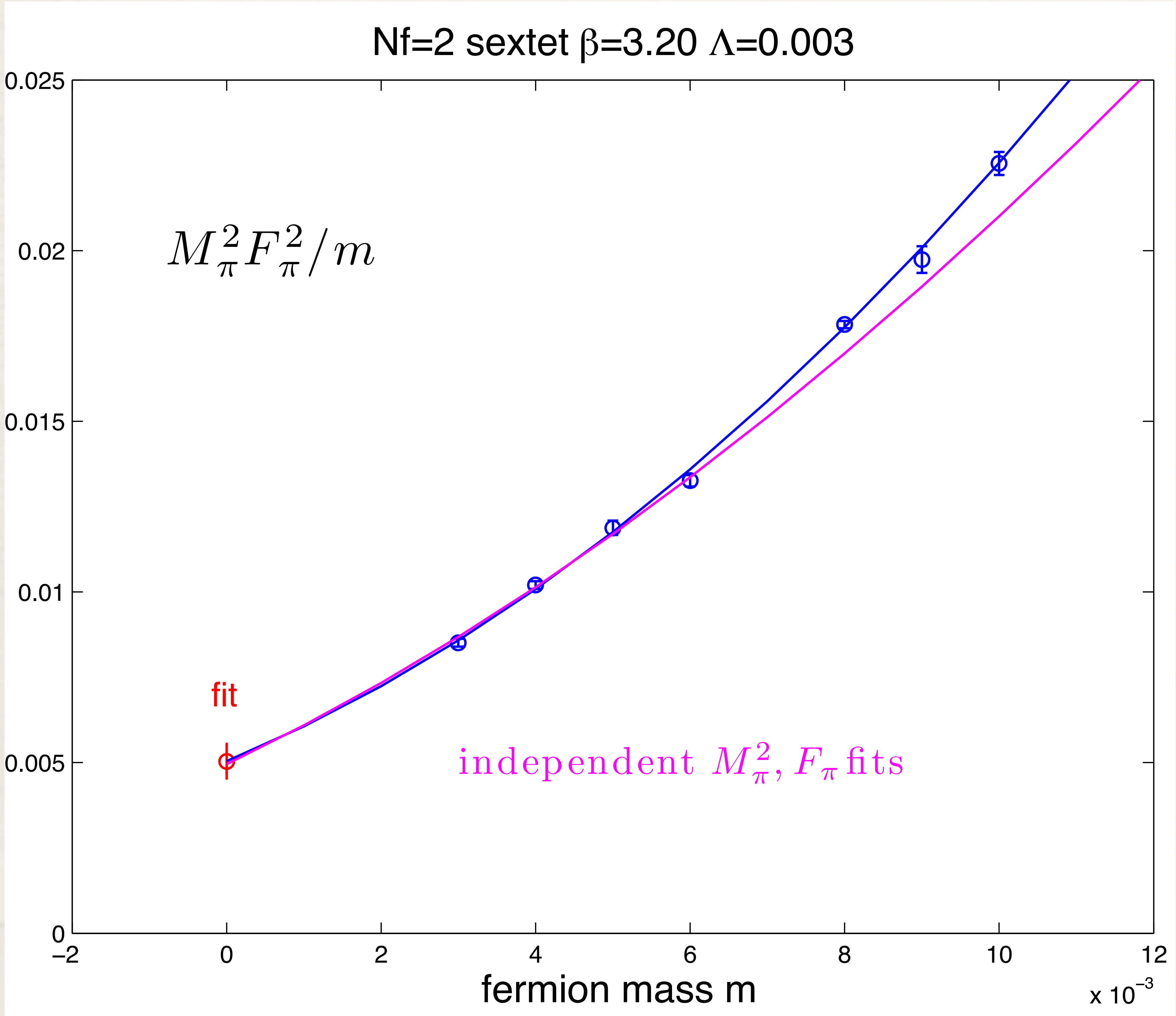
$$\left[1 - m_{\rm v}\frac{d}{dm_{\rm v}}\right]\langle\bar\psi\psi\rangle\Big|_{m_{\rm v}=m} = \langle\bar\psi\psi\rangle - m\cdot\chi_{con}$$

removes dominant linear term

both observables non-zero in chiral limit

can we do better?

GMOR



GMOR relation $\langle\bar\psi\psi\rangle = 2BF^2$

$$M_\pi^2 = 2B\cdot m$$

rearrange

$$\langle\bar\psi\psi\rangle = M_\pi^2 F_\pi^2/m$$

magenta combine previous fits of M_π^2, F_π

red separate fit of $M_\pi^2 F_\pi^2/m$ data
quadratic ; larger data set

both methods consistent

value of condensate in chiral limit smaller than from extrapolations of directly measured condensate, even with subtraction

is staggered chiral PT required to achieve consistency?

eigenvalues

Euclidean, continuum Dirac operator eigenvalues $i\lambda_k$

density $$\rho(\lambda, m) = \frac{1}{V} \sum_{k=1}^{\infty} \langle \delta(\lambda - \lambda_k) \rangle$$

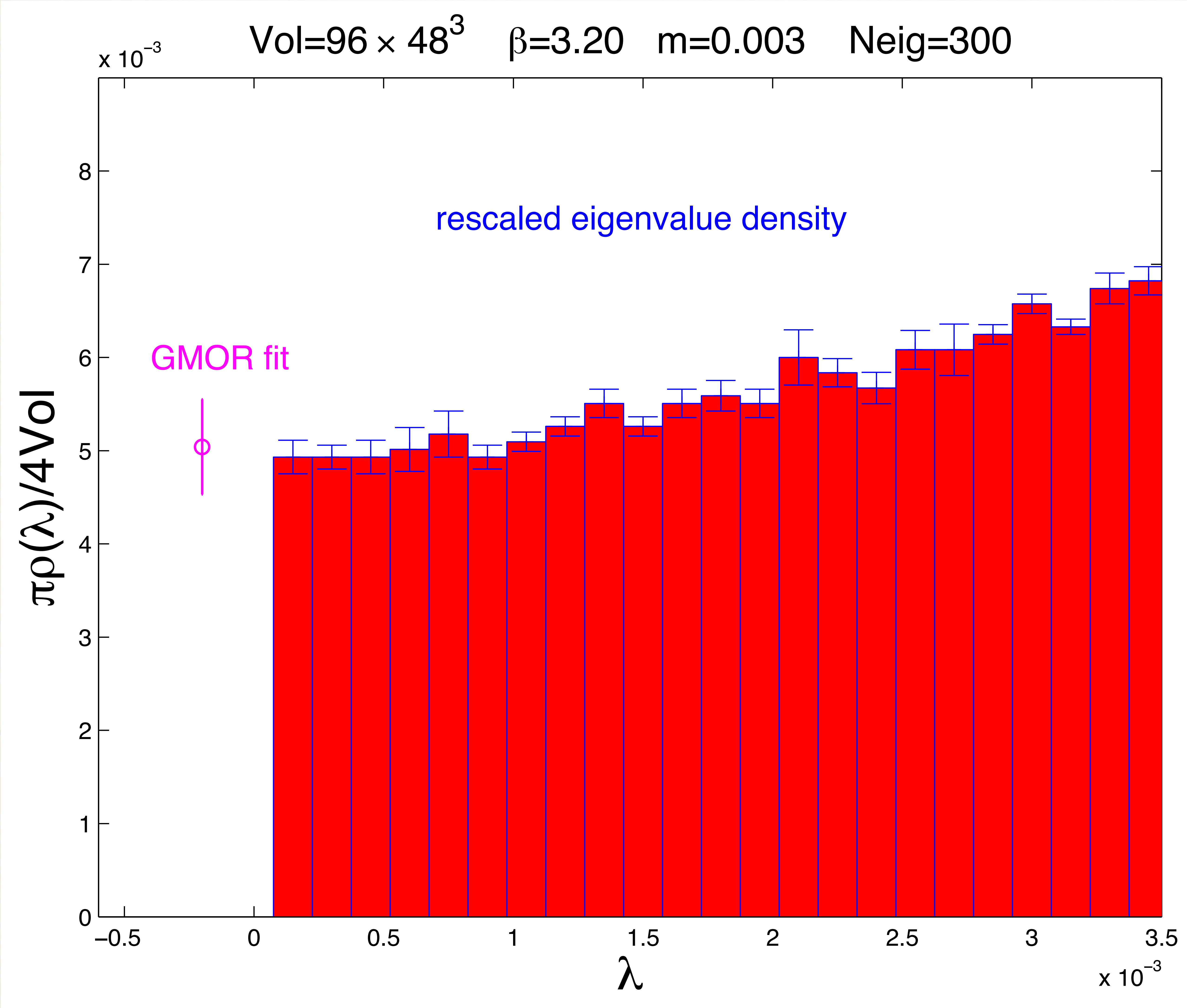
Banks-Casher $$\lim_{\lambda \to 0} \lim_{m \to 0} \lim_{V \to \infty} \rho(\lambda, m) = \frac{\Sigma}{\pi}$$ $$\Sigma = -\langle \bar{\psi} \psi \rangle$$

relevant for simulations at finite mass and volume?

absence of near-zero modes due to too small volume can occur

calculate lowest eigenvalues numerically directly for various ensembles

eigenvalue density



calculate lowest eigenvalues over range mass, volume

show here largest volume and lightest mass

near-zero modes *do* condense

numerical value agrees well with GMOR determination

Banks-Casher in simplest form appears to work

mode number

more sophisticated version: eigenvalues of $D^\dagger D + m^2$ Giusti & Luscher '08

count number of eigenvalues $\leq M^2$

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

mode number $\nu(M,m)$ is renormalization-group invariant

leading order chiPT

$$\Sigma_{\rm eff} = \frac{\pi}{2} \frac{\nu(M,m)}{\Lambda V}$$

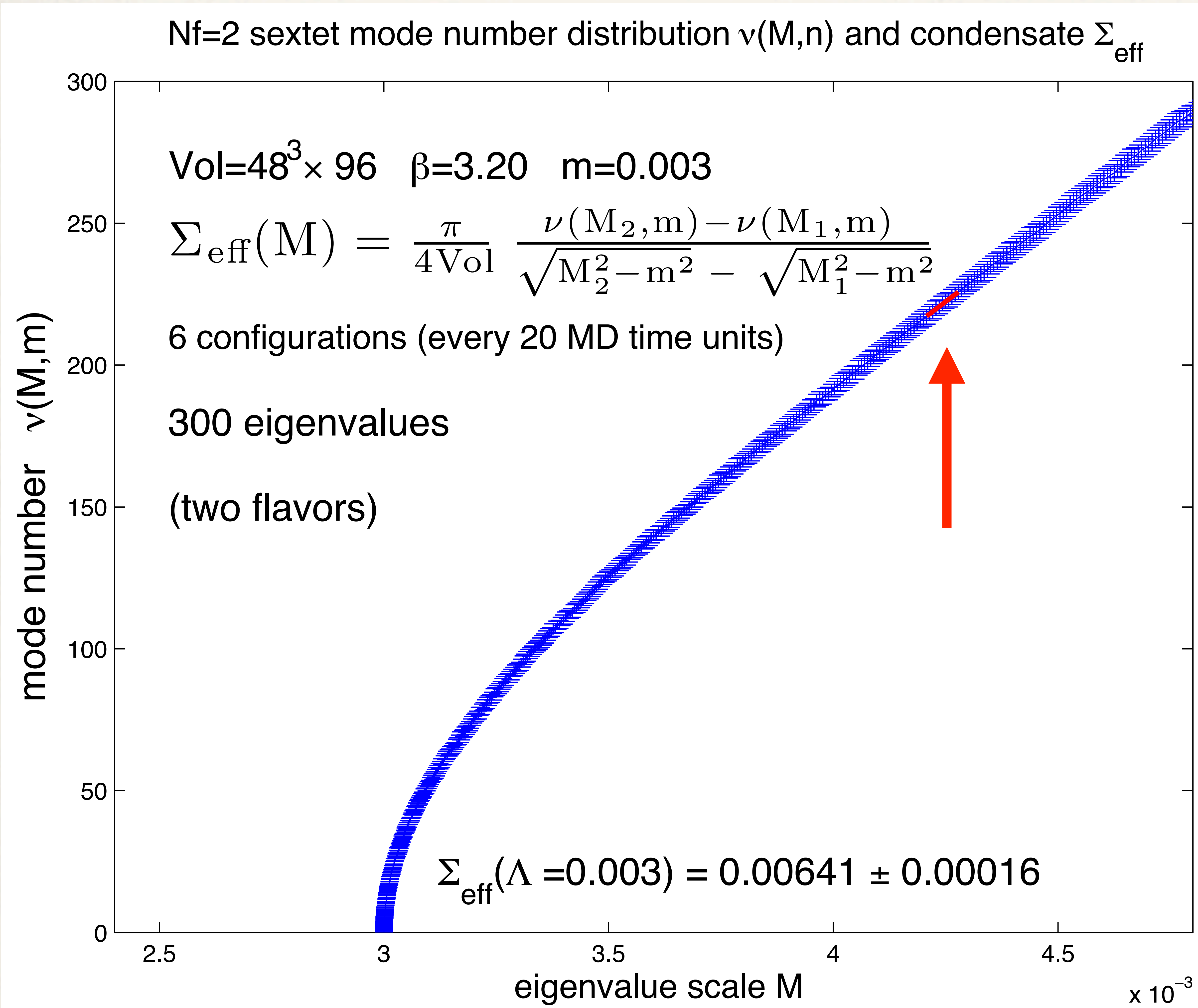
For $N_F = 2$ 1-loop chiPT correction is zero in chiral limit for any value of scale Λ Smilga & Stern '93

$N_F = 2$ QCD simulations mild quark mass dependence of mode number

chiral extrapolation linear

(G&L also present stochastic method to measure mode number)

mode number



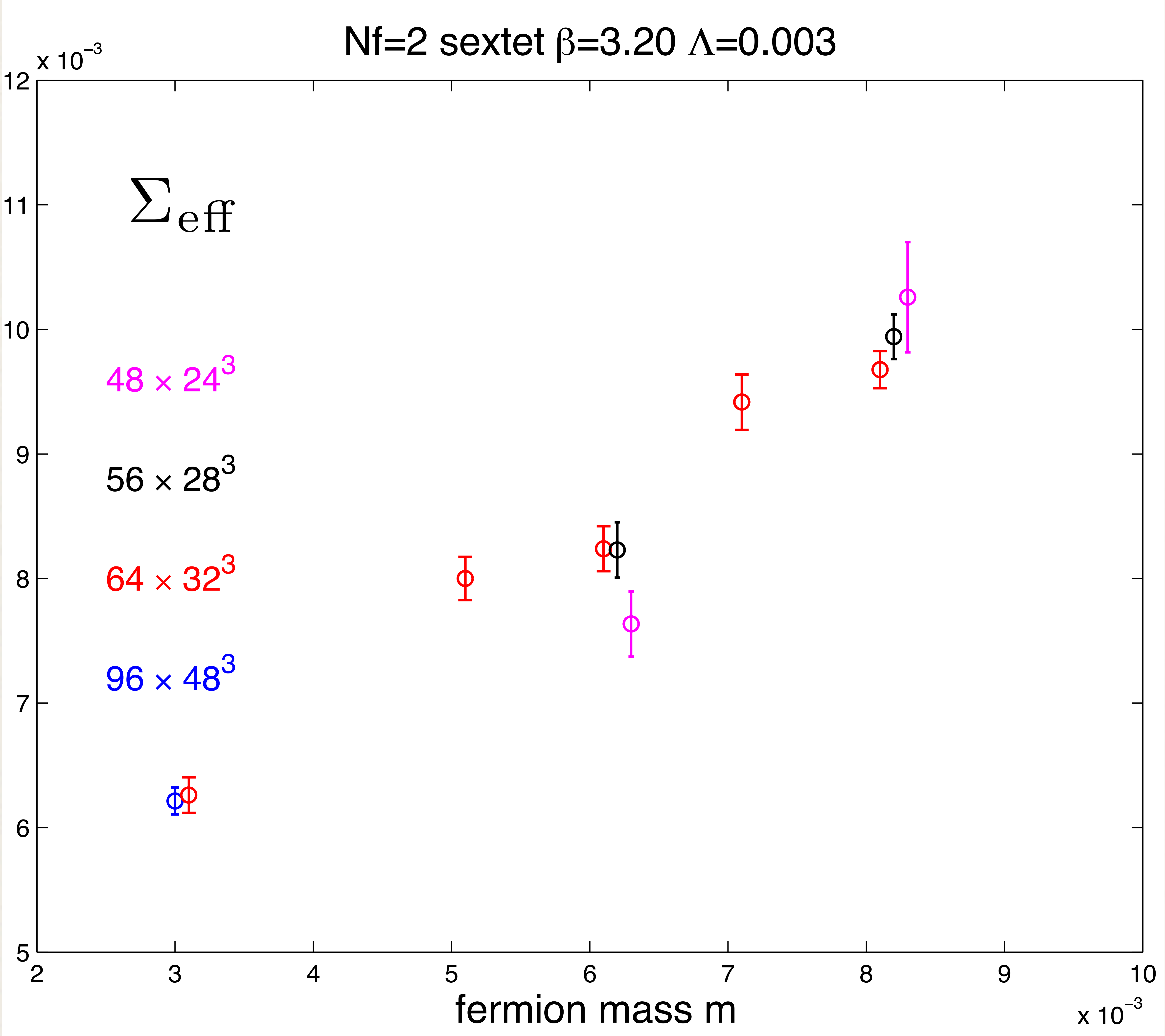
choose scale Λ which overlaps many mass, volume ensembles

define

$$\Sigma_{\mathrm{eff}} = \frac{\pi}{4V} \frac{d\nu(M,m)}{d\Lambda}$$

red corresponds to $\Lambda = 0.003$

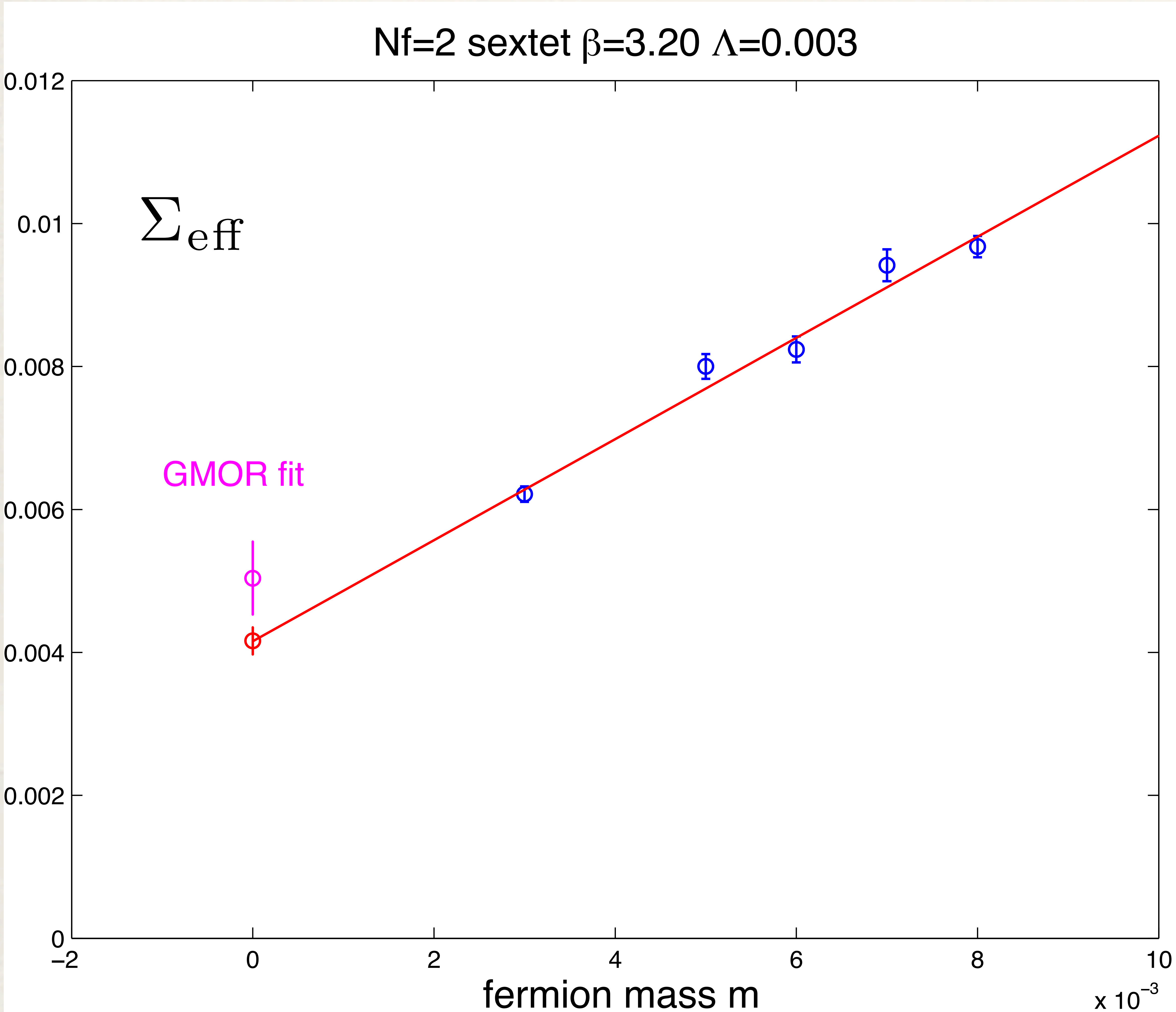
volume dependence



sensitivity to volume appears to be under control

treat data on largest volume at each mass as effectively infinite volume

chiral extrapolation



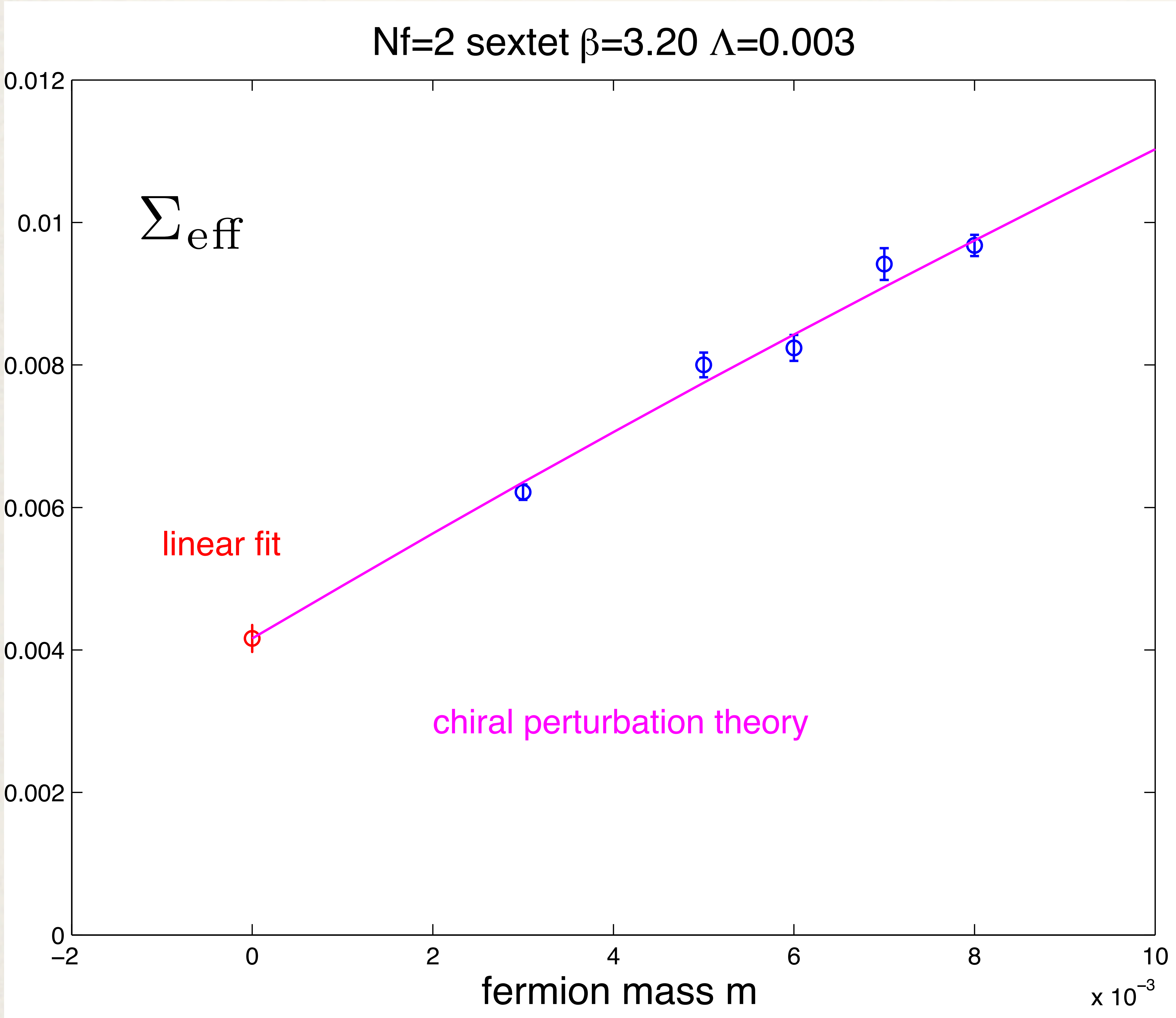
fit data at largest volumes only

linear dependence on mass describes the data well

extrapolated value in reasonable agreement with GMOR

chiral PT comparison

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



$$\mu = \frac{F^2 M_{\rm mom}^2}{2\Sigma}$$ momentum cutoff

Osborn, Toublan & Verbaarschot '98

red linear extrapolation

chiral PT expansion around zero mass appears to agree with linear extrapolation from non-zero mass

summary

eigenvalues and mode number study new and unfinished

steep mass dependence of condensate reduced

chiral extrapolation: non-zero condensate → supports chiral SB picture

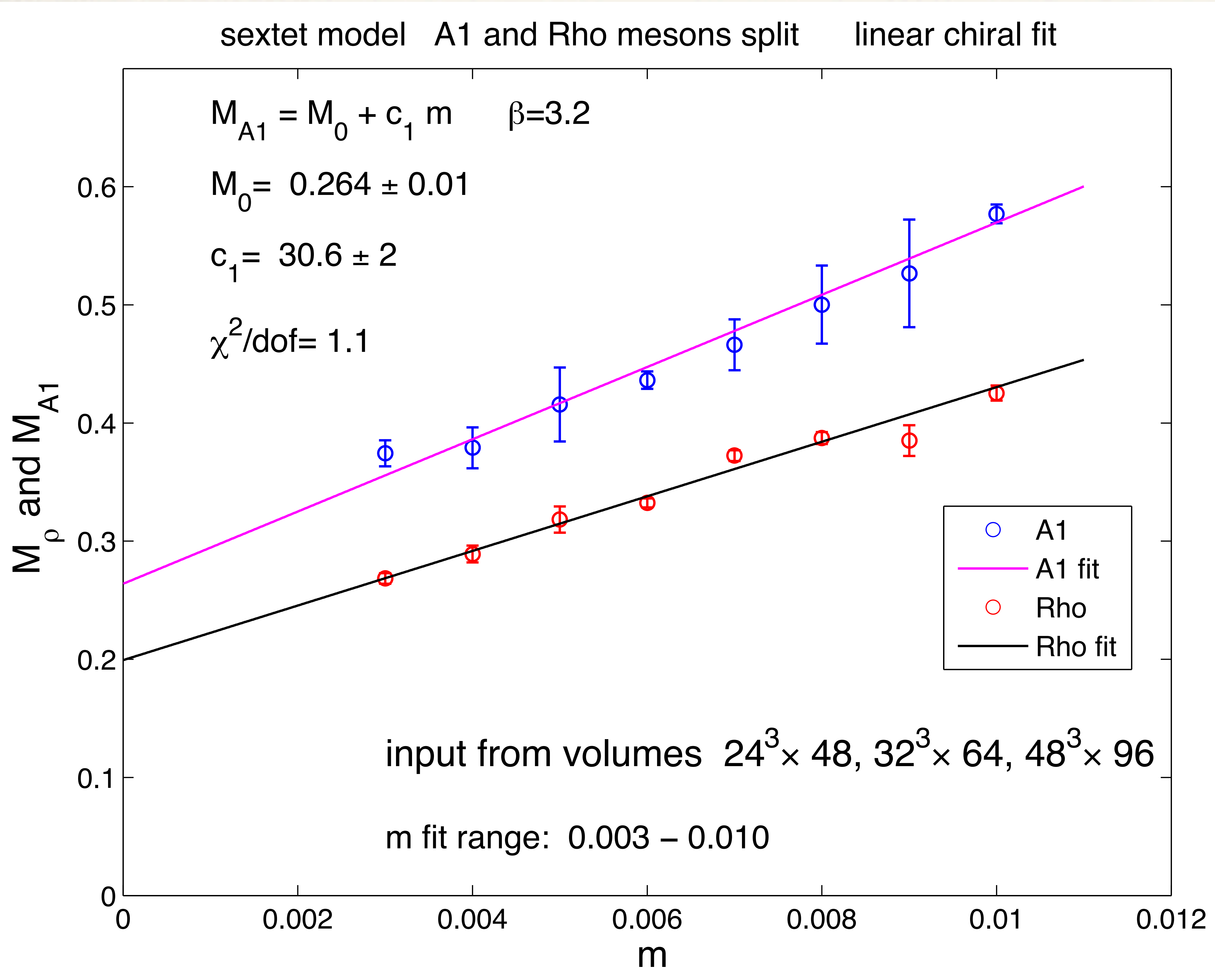
improvement in consistency between GMOR relation and direct chiral condensate

coming soon: full implementation of gradient flow (including fermion flow)

gradient flow running coupling

back-up slides

mass spectrum

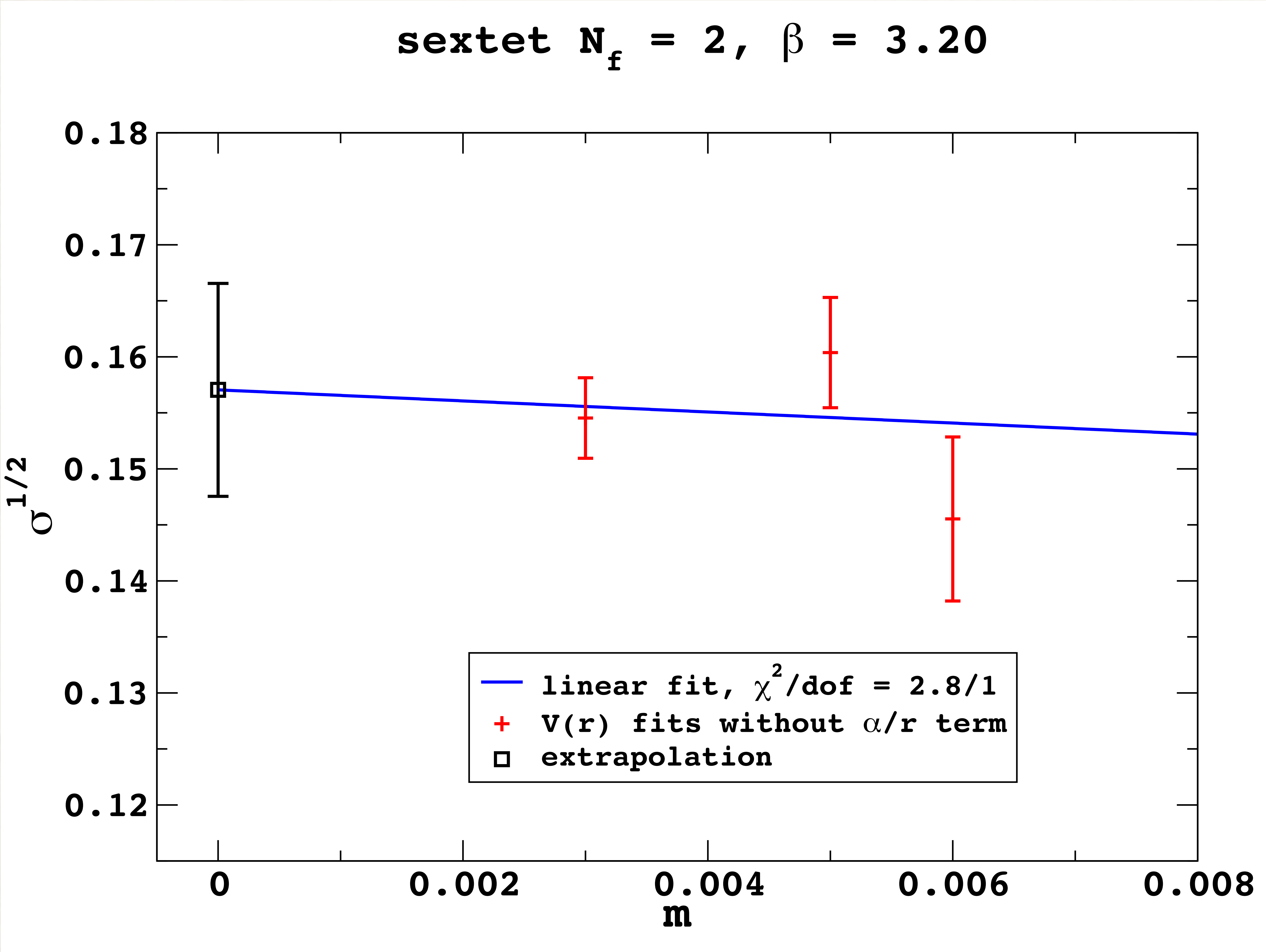


scale: F = 0.0279(4)

convert via F = 246 GeV

vector ~ 1.7 TeV
axial vector ~ 2.3 TeV

static fermion potential



PoS 2012, 1211.3548

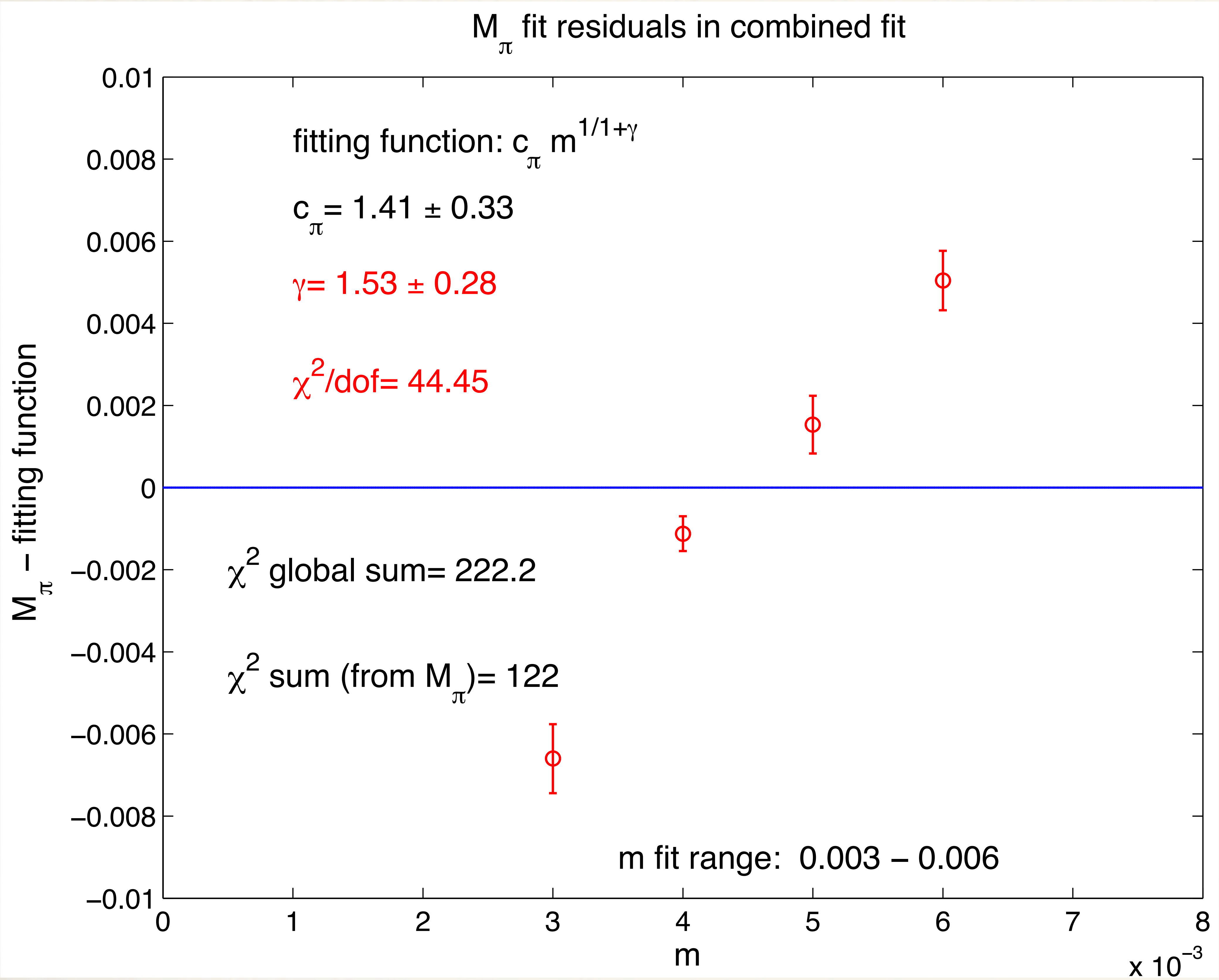
linear behavior in fermion potential at larger separation

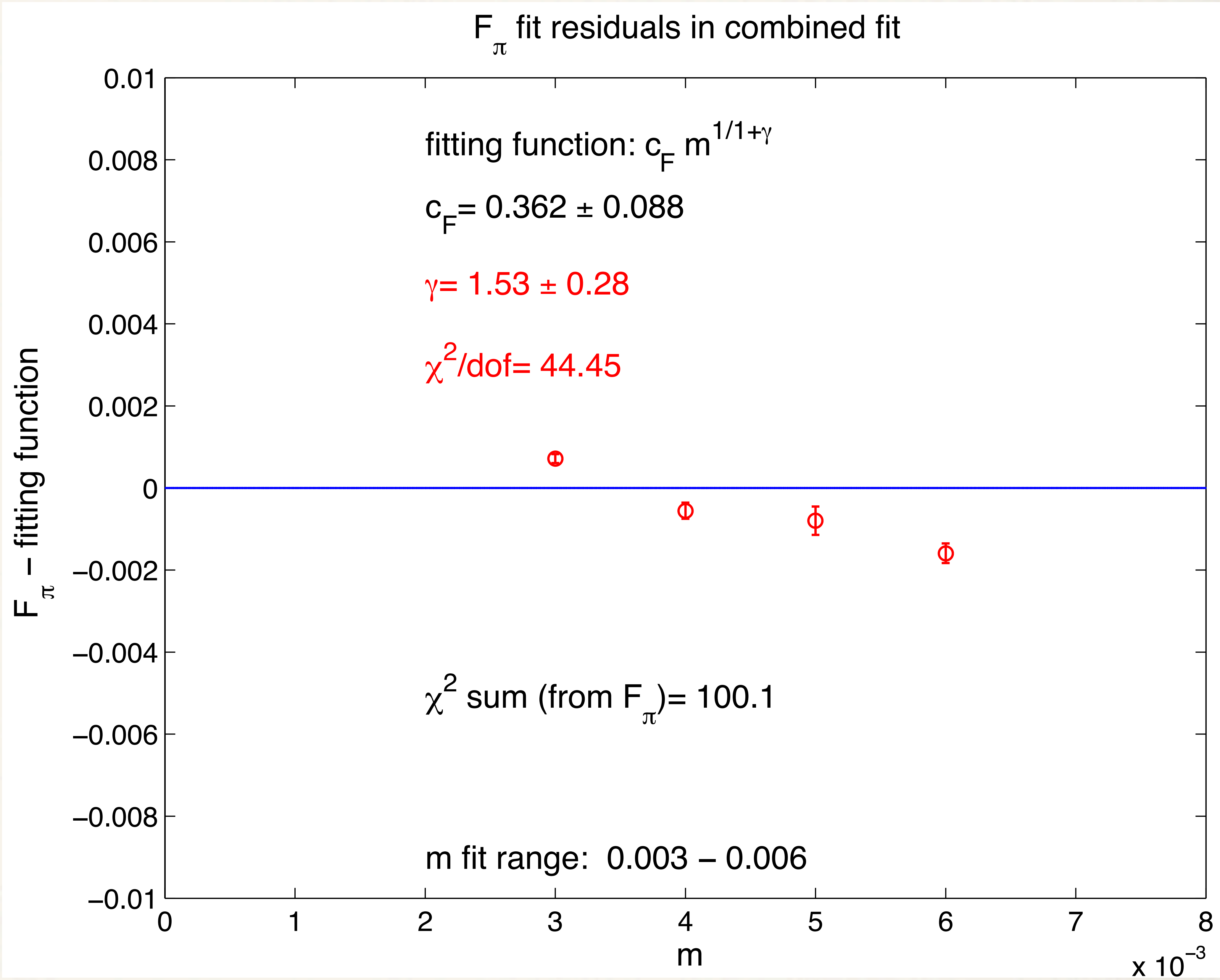
string tension insensitive to fermion mass

non-zero in chiral limit

further evidence theory is not conformal

conformal hypothesis

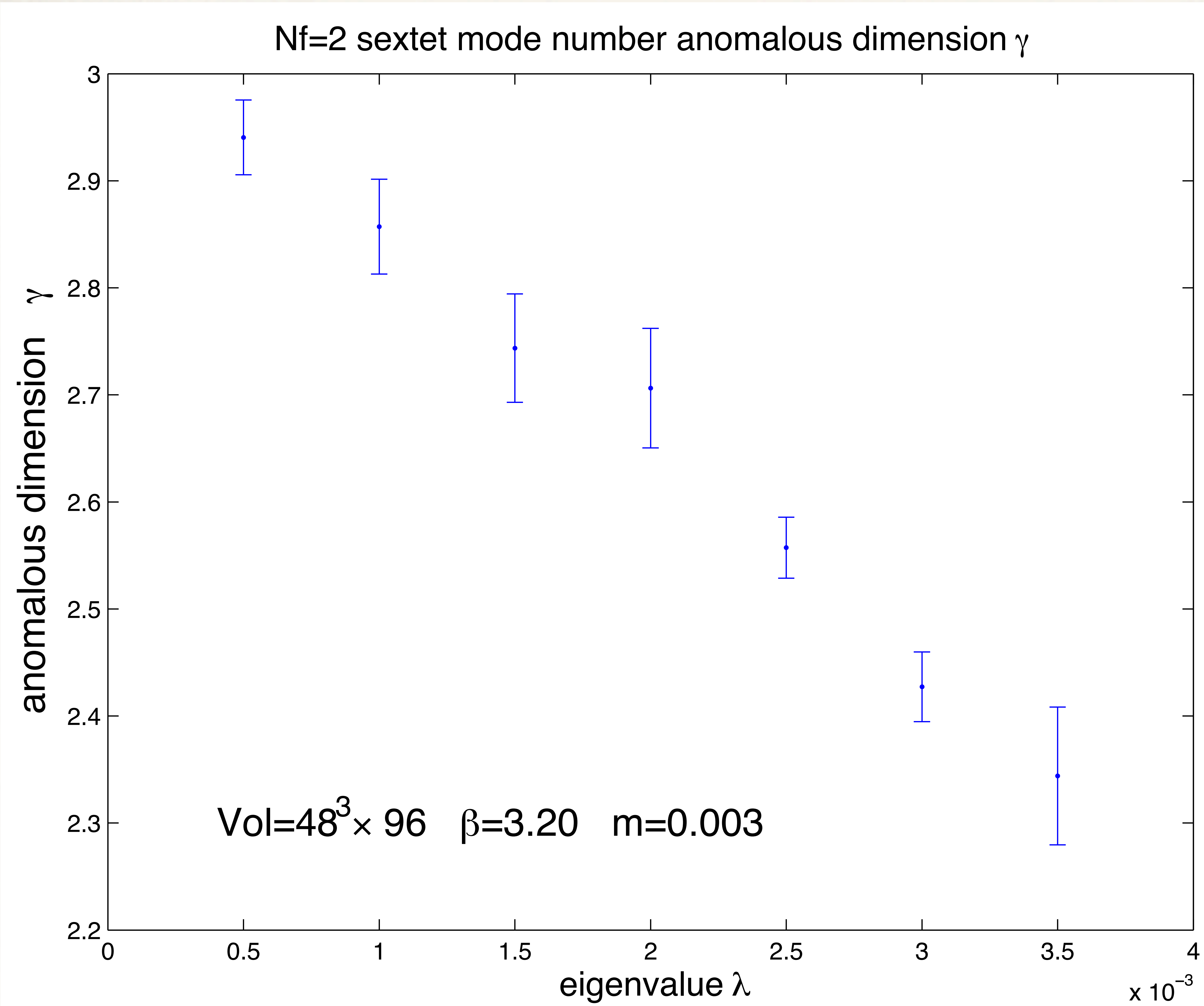




cannot describe data with universal value of exponent

conformal hypothesis fails

eigenvalue density + anomalous dimension



mode number of eigenvalues of massless Dirac operator

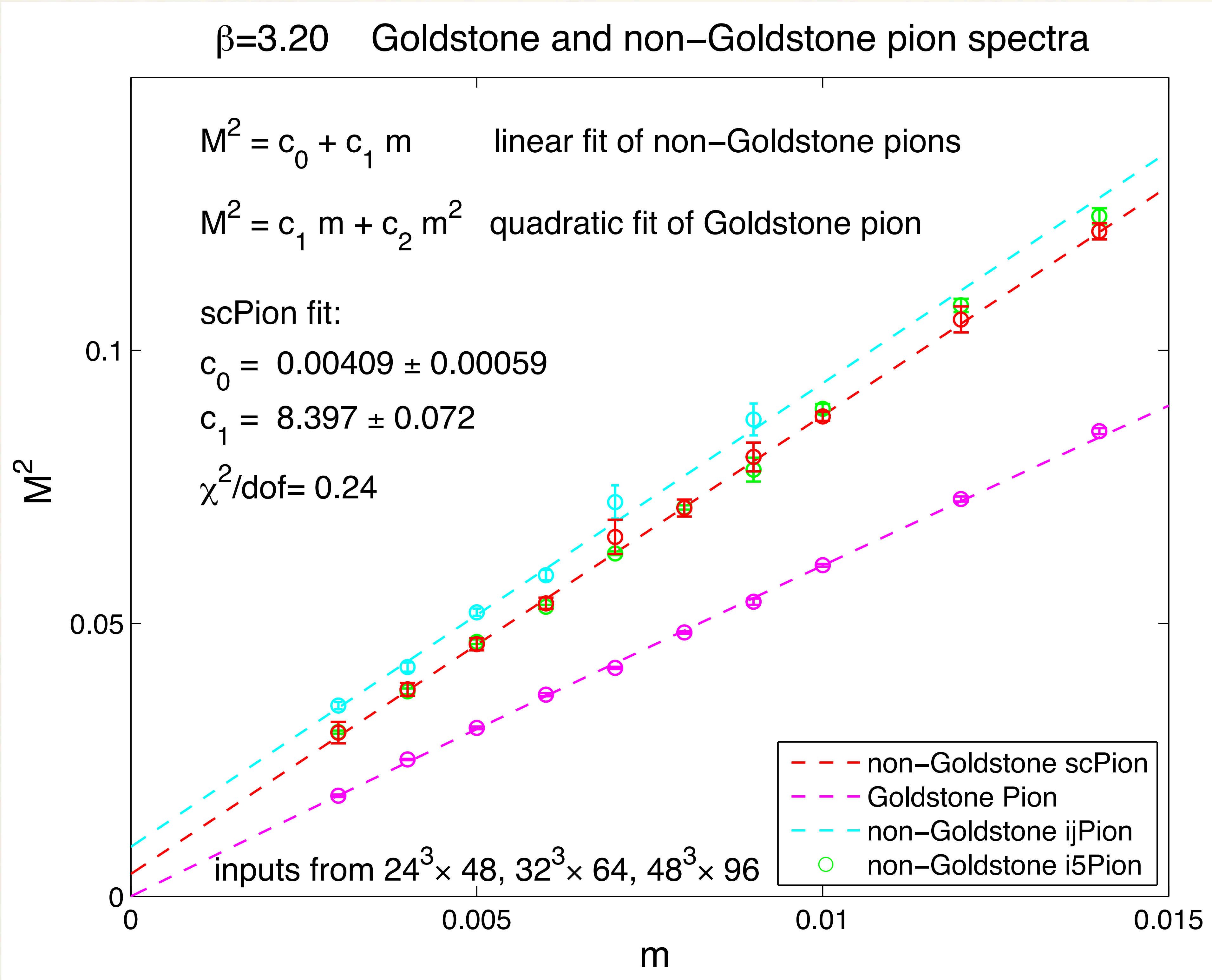
$$\nu(\lambda) = V \int_{-\lambda}^{\lambda} d\lambda' \, \rho(\lambda')$$

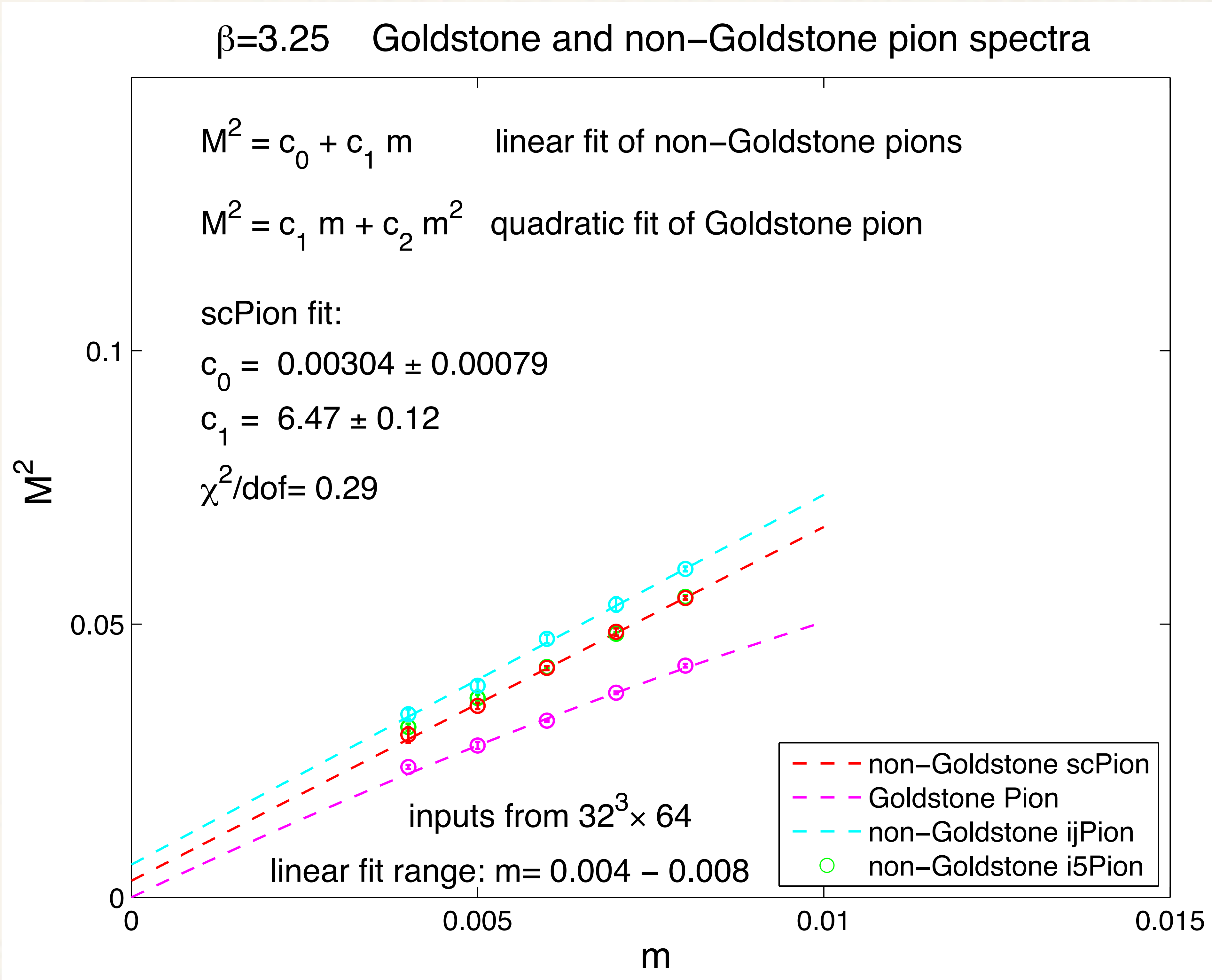
if theory is conformal

$$\nu(\lambda) \propto \lambda^{1+\alpha}, \quad 1+\alpha = 4/(1+\gamma)$$

measure via derivative

taste breaking





split between Goldstone bosons due to lattice artifacts

similar in magnitude to lattice QCD simulations with staggered fermions e.g. HPQCD