Gluonic Excitations and String Theory

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Workshop on Gluonic Excitations
May 14, 2003, Jefferson Laboratory

Collaborators:
Jimmy Juge Bern
Colin Morningstar Carnegie Mellon

Contribution from:
Mike Peardon Dublin

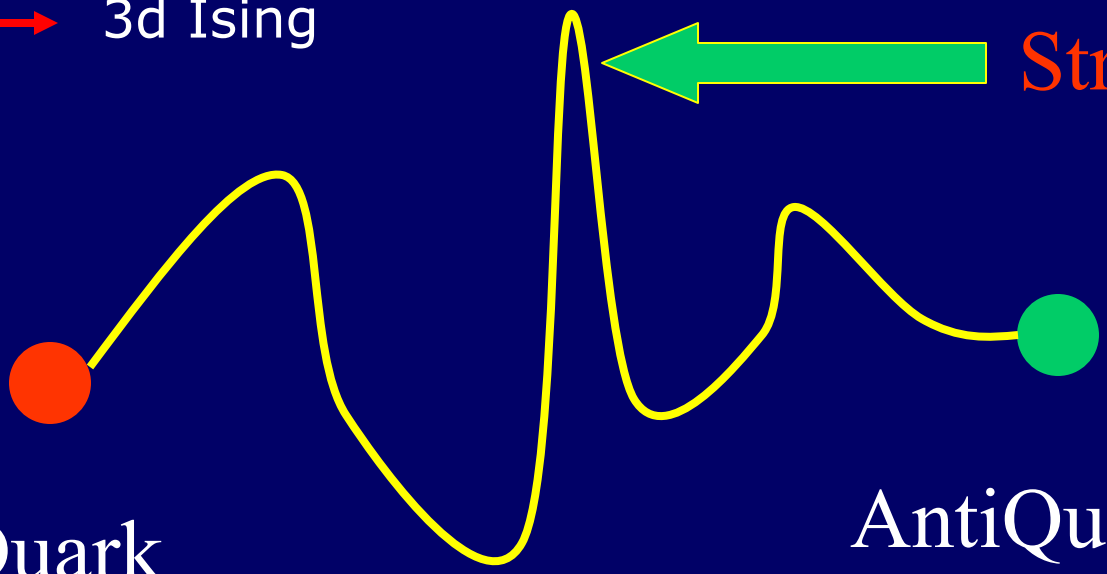
String Counselor:
Ken Intriligator UCSD

Confining Force

Polyakov Z(2) gauge model
duality ⟷ 3d Ising

What is this stuff?
String?

QCD?



Quark

AntiQuark

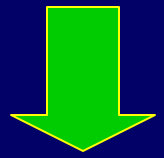
String theorists are interested in the problem

Quenched, relevant in large N limit

Early work:

Polyakov
Luscher
Polchinski, Strominger
Michael
Teper
Gliozzi et al.
Hasenbusch, Pinn
JKM (old)
Baker et al.
Munster
…

This talk: tutorial on the paper



New work:

Juge, JK, Morningstar → spectrum with fine structure
HEP-LAT 0207004 PRL 90 (2003) 161601

Luscher, Weisz → ground state Casimir energy
HEP-LAT 0207003 JHEP 0207 (2002) 049

created "Casimir energy paradox"

Space-time dimension

$$\frac{1}{2}\sum_{n=1}^{\infty} n = -\frac{\pi}{24}(d-2)$$

smart enough
for string theory?

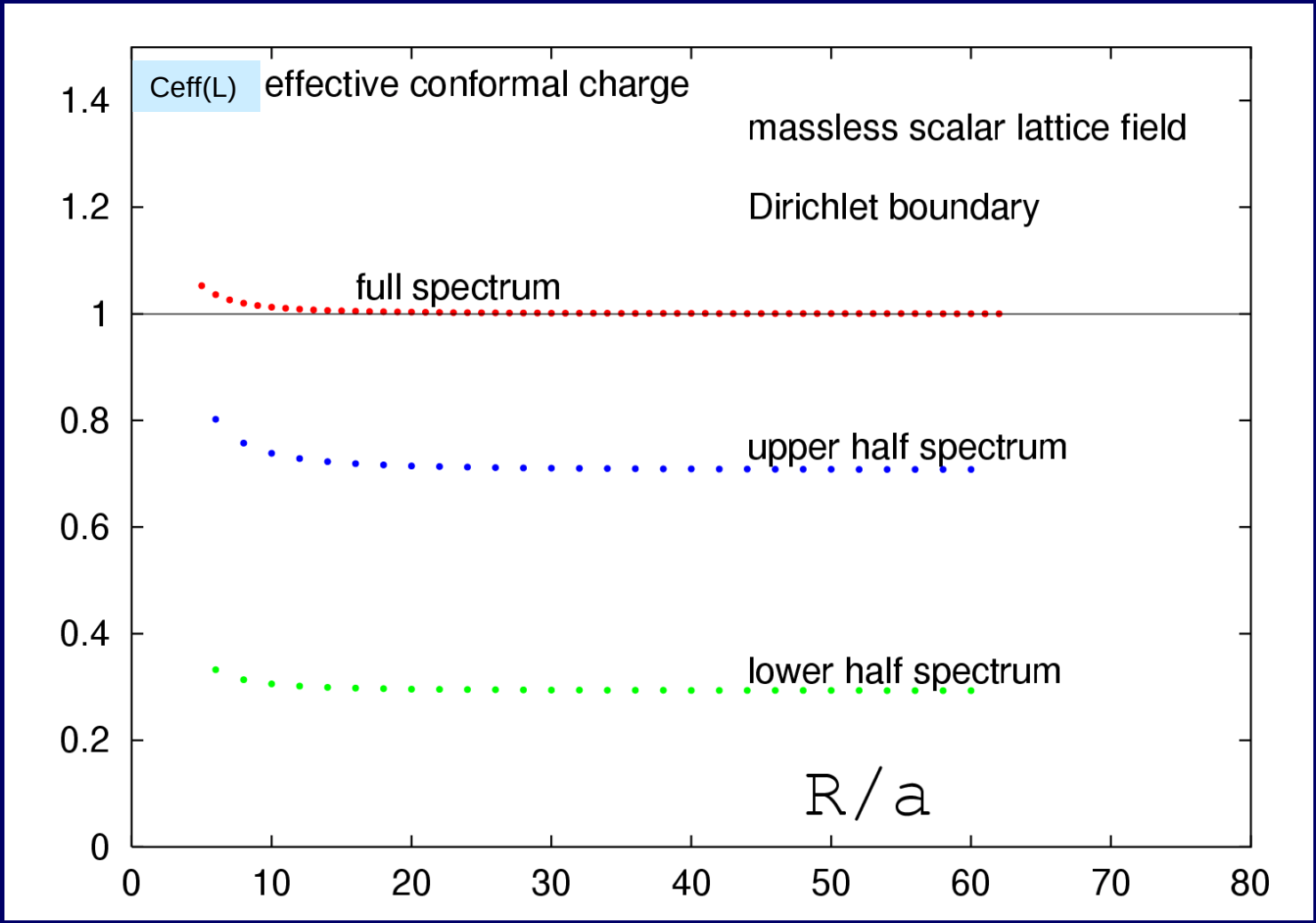
This is NOT a paradox

We turn to the lattice for learning how to do the sum:

$$E_{reg}(L,a) = \frac{2L}{\pi a^2} - \frac{1}{2a} - \frac{\pi}{24L} + O(a^2)$$

$$E_{reg}(L,a) = \frac{2L}{\pi a^2} - \frac{1}{2a} - \frac{\pi}{24L} + O(a^2)$$

$C_{eff}(L) = -12L^3 E_{reg}''(L,a)/\pi$



LW makes math even harder:

$$\frac{1}{2}\sum_{n=1}^{3} n = -\frac{\pi}{24}(d-2)$$

This IS a paradox!

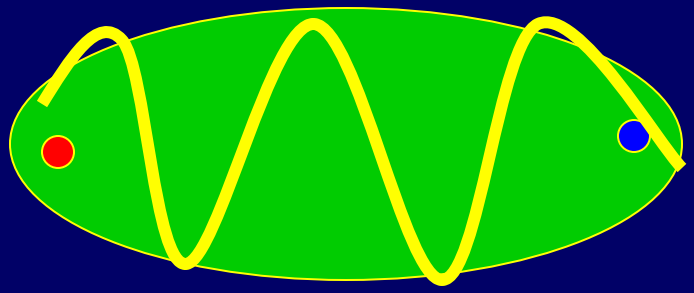
OUTLINE

1. QCD String Spectrum
   - spectrum
   - Casimir energy
   - the paradox
2. Z(2) string
   - phase diagram and surface criticality
   - spectrum
   - systematic loop expansion
   - Casimir energy
3. Conclusions

For applications to hybrids -> Morningstar's talk

TwentyTHIRD anniversary of the first paper on heavy $Q\bar{Q}$gluon states:

P. Hasenfratz, R. Horgan, JK, J.Richard
Phys. Lett. B95, 299, 1980

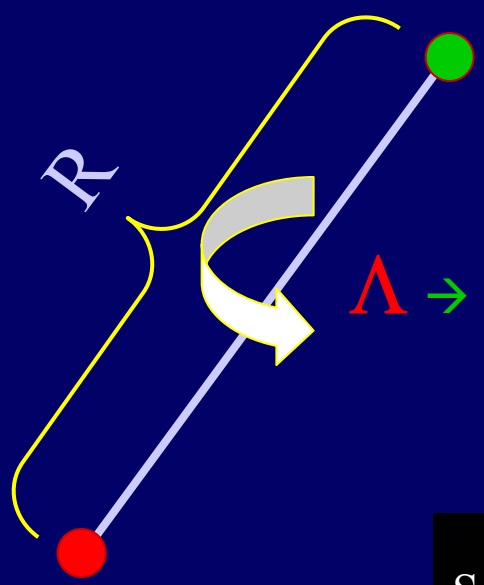


TE and TM gluon

Hybrid π_u potential was calculated

Born-Oppenheimer picture was developed for exotic and non-exotic states

Predictions hold today



Opposite fixed color source (antiquark)

Λ → angular momentum projected along quark-antiquark axis

Fixed color source (quark)

S states (Λ =0)	Σ_g^{+-}
P states (Λ =1)	Π^{+-}
D states (Λ =2)	Δ^{+-}
⋮	

Three exact quantum numbers characterize gluon excitations:

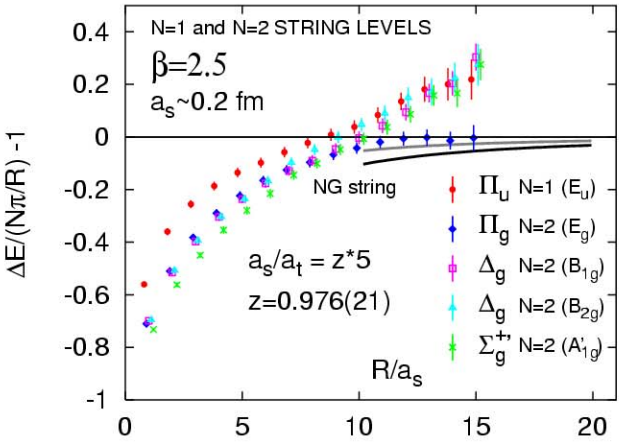
Λ^{+-} **Angular momentum with chirality**

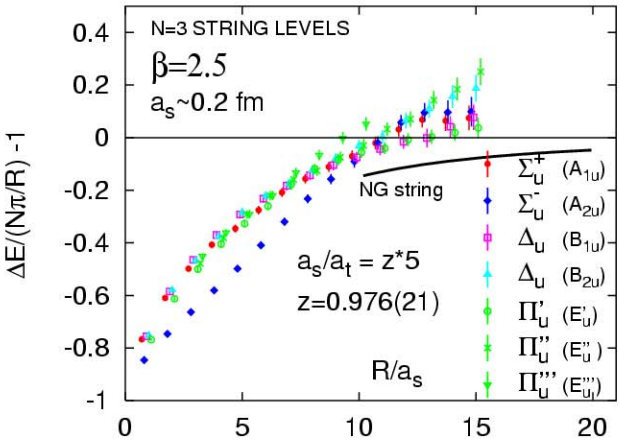
$+-$ **Chirality, or reflection symmetry for $\Lambda = 0$**

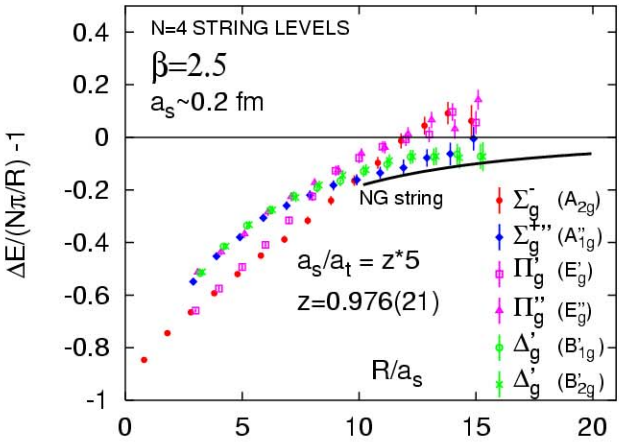
CP

g (gerade) **CP even**

u (ungerade) **CP odd**







D=4 SU(3)

All results are quenched

19 states in 0.2 fm - 3 fm range

Very complex spectrum

Searching for string limit?

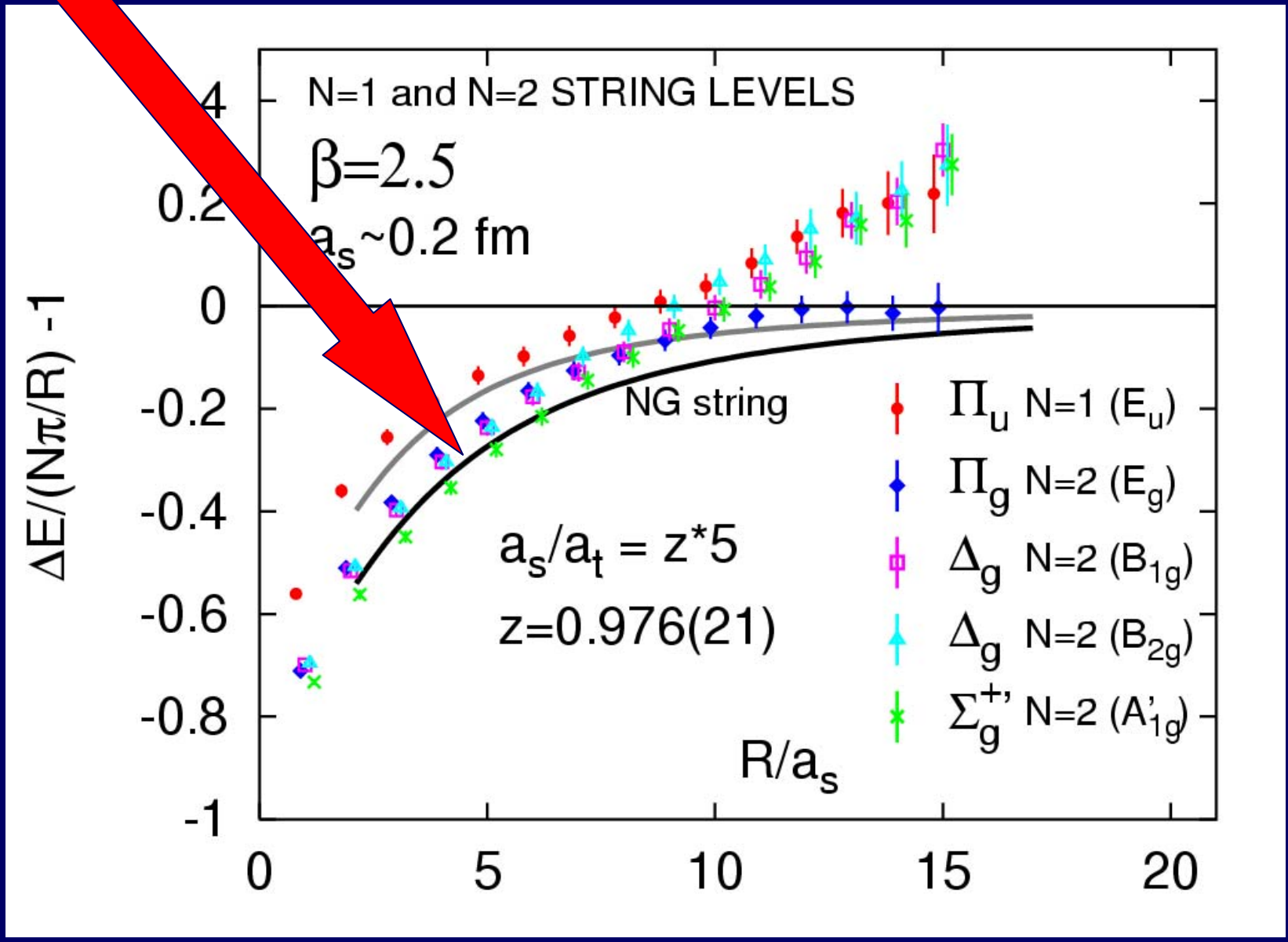
for reference:

Nambu-Goto Bosonic string:

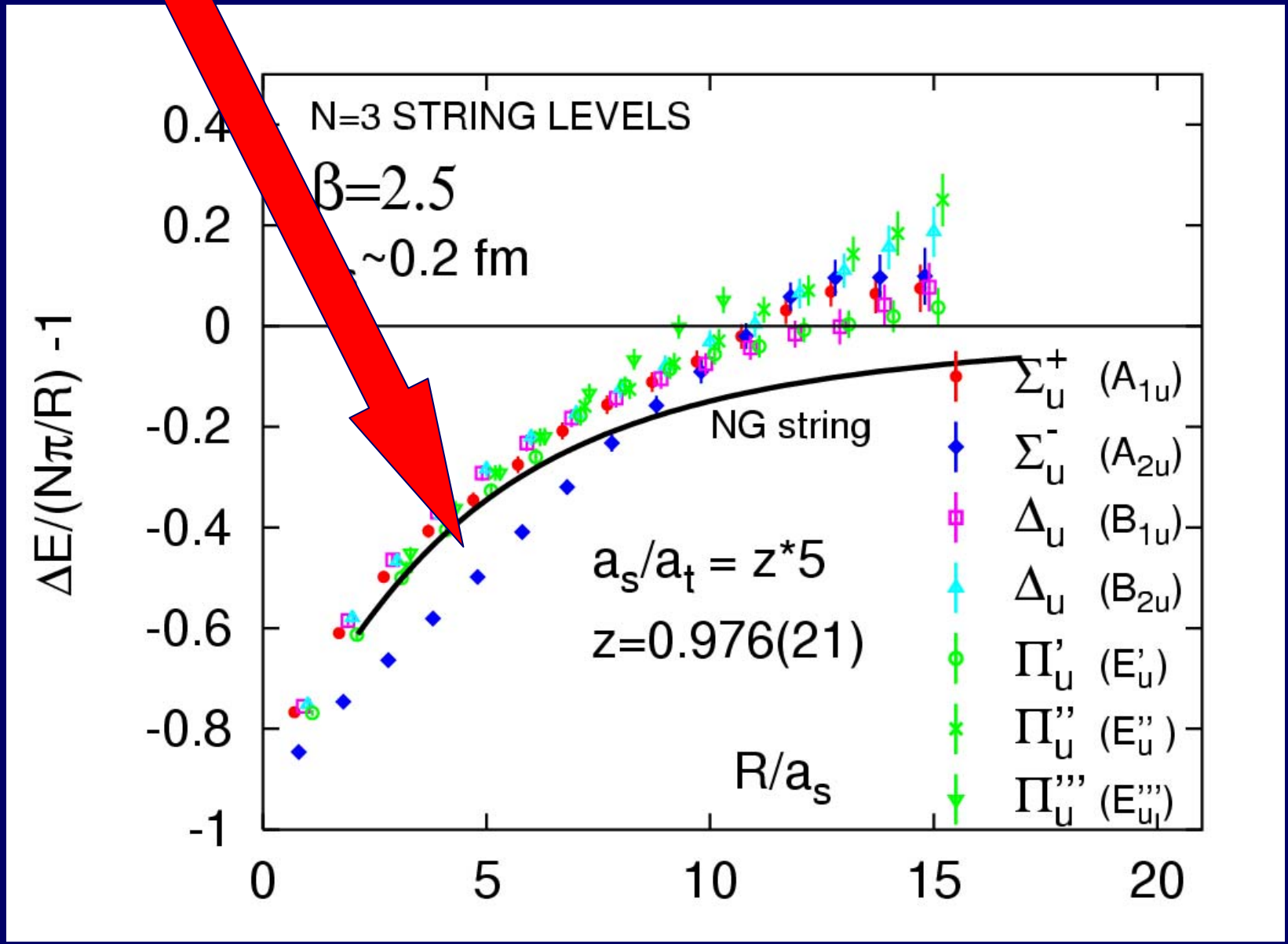
tachion problem

$$E_N = \sigma R\left[1-\frac{D-2}{12\sigma R^2}\pi+\frac{2\pi N}{\sigma R^2}\right]^{\frac{1}{2}}$$

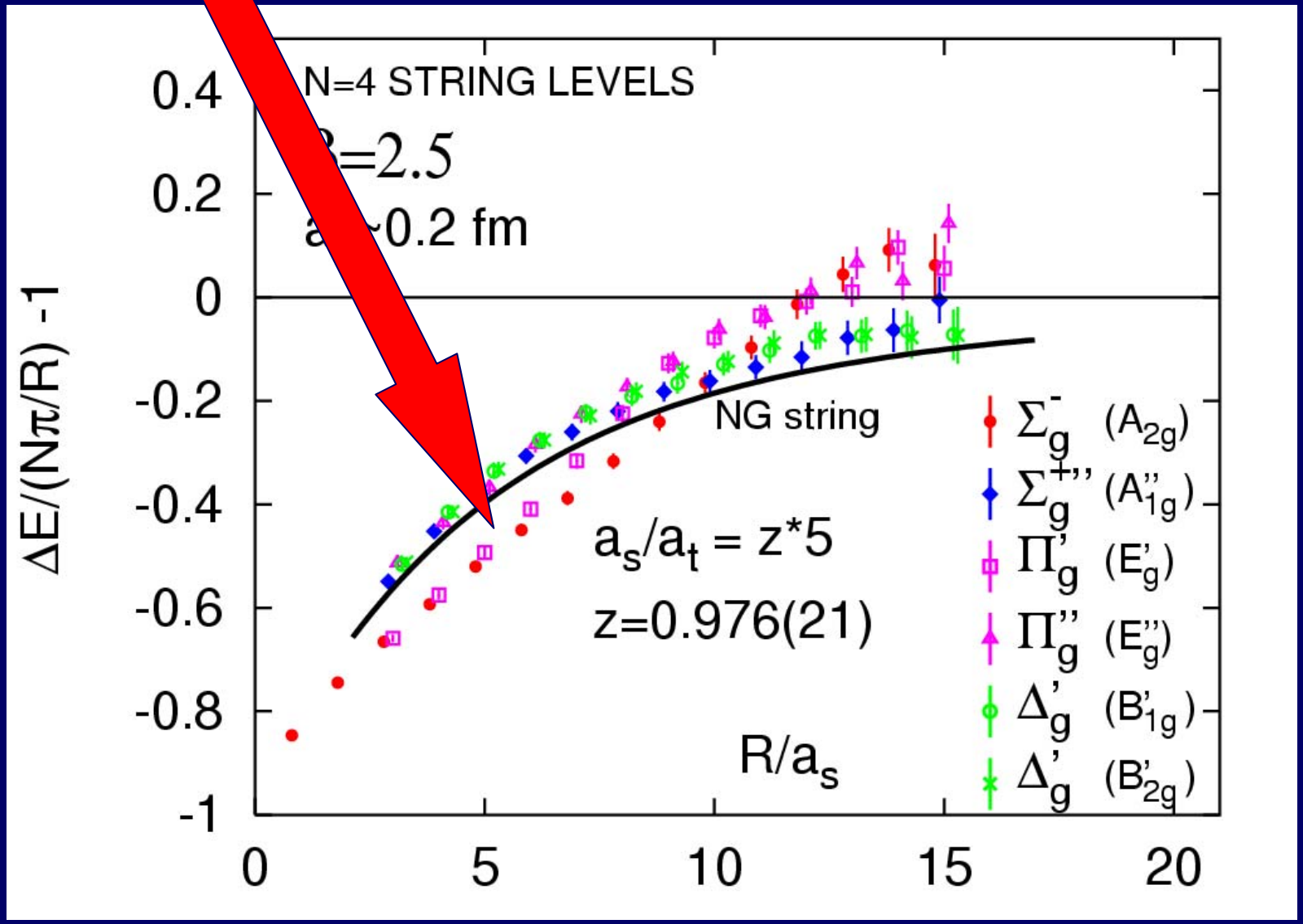
NG string fails in fine structure (and it should!)

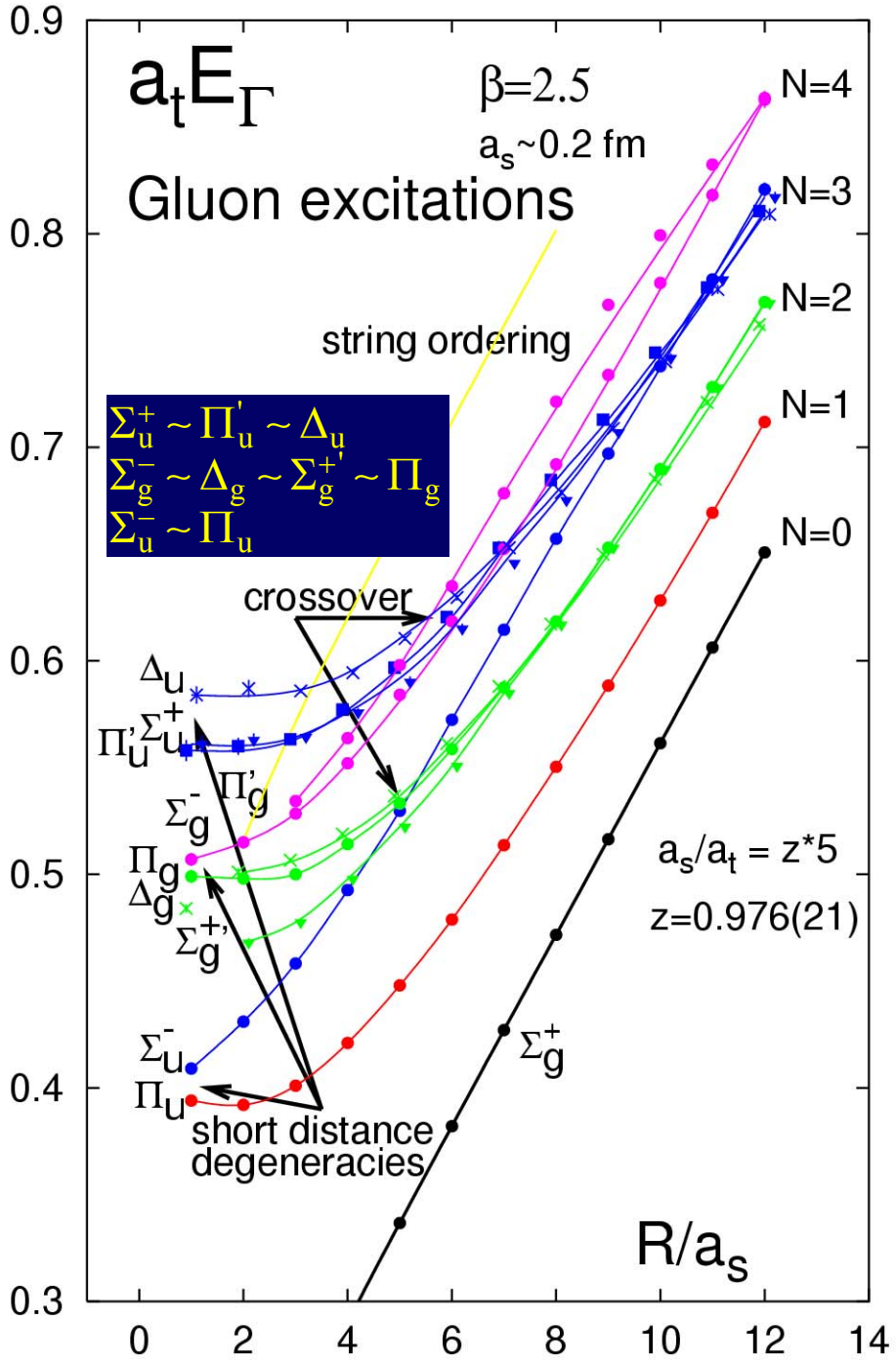


NG string fails in fine structure (and it should!)



NG string fails in fine structure (and it should!)





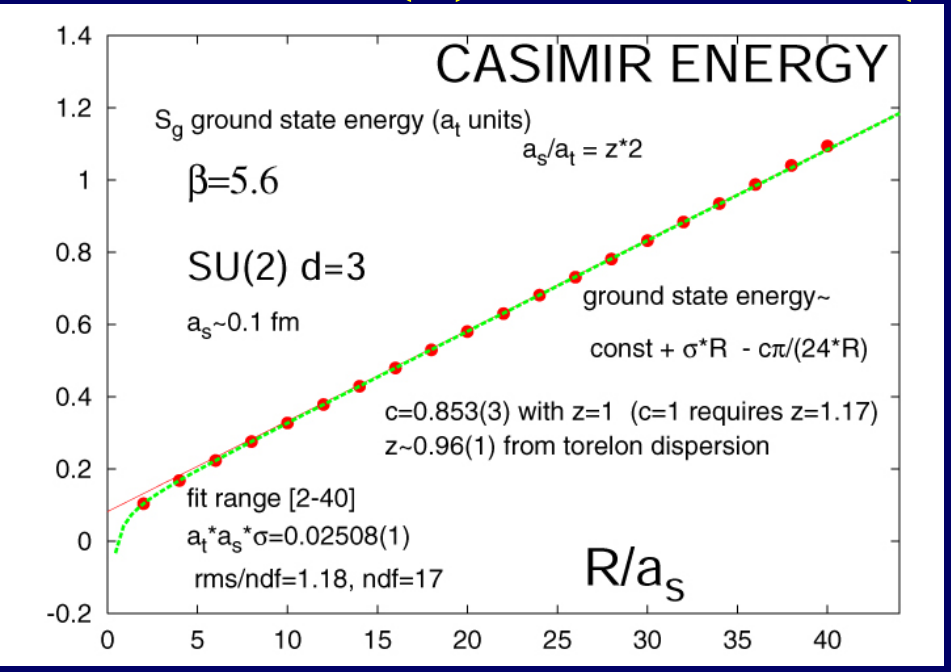
Three length scales in energy spectrum:

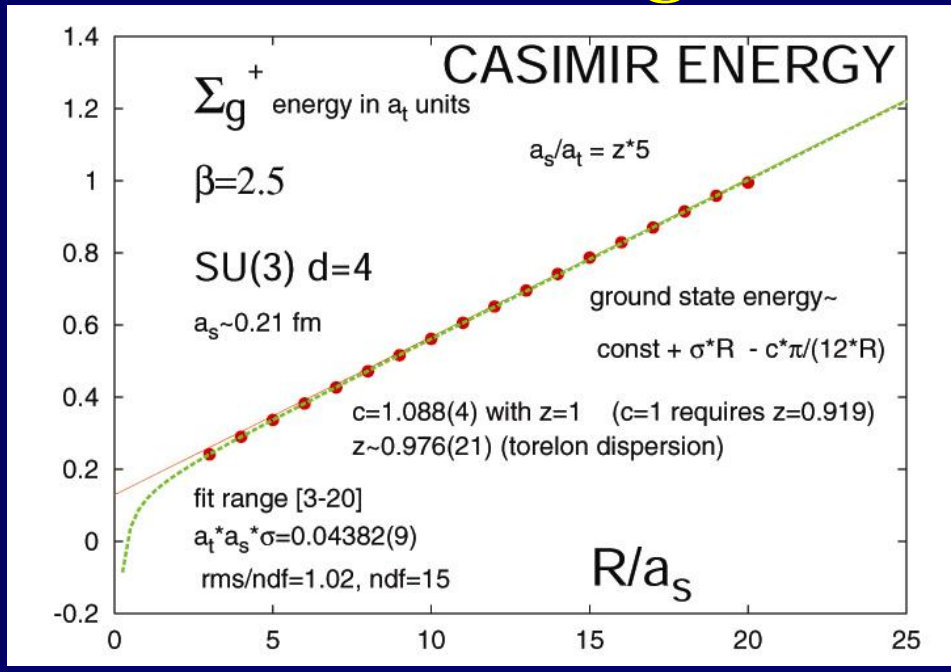
R < 0.5 fm approximate spherical symmetry
Bag-like "anti-string" picture
Short distance QCD Bag picture
OPE Soto et al.

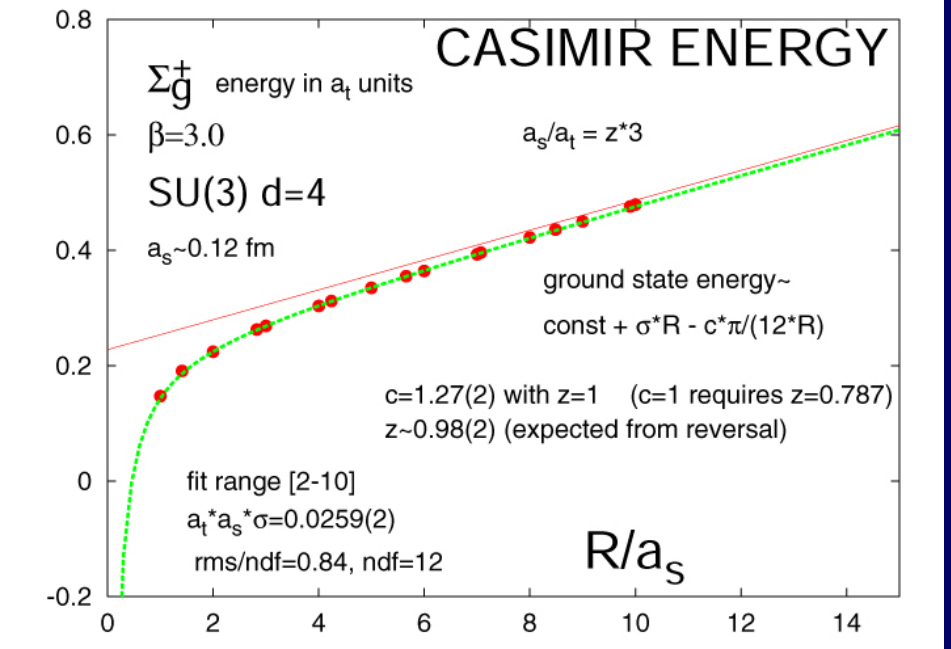
R ~ 0.5 fm – 1.5 fm
Crossover (model sensitive)

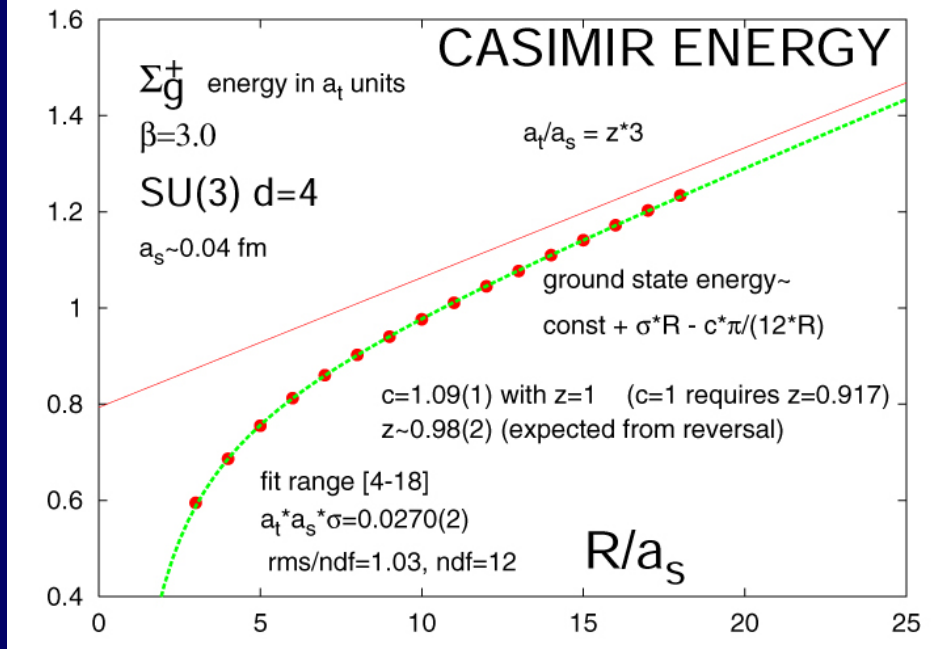
R ~ 2 fm - 3 fm
Onset of string ordering

3d SU(2) and 4d SU(3) Conformal Charges



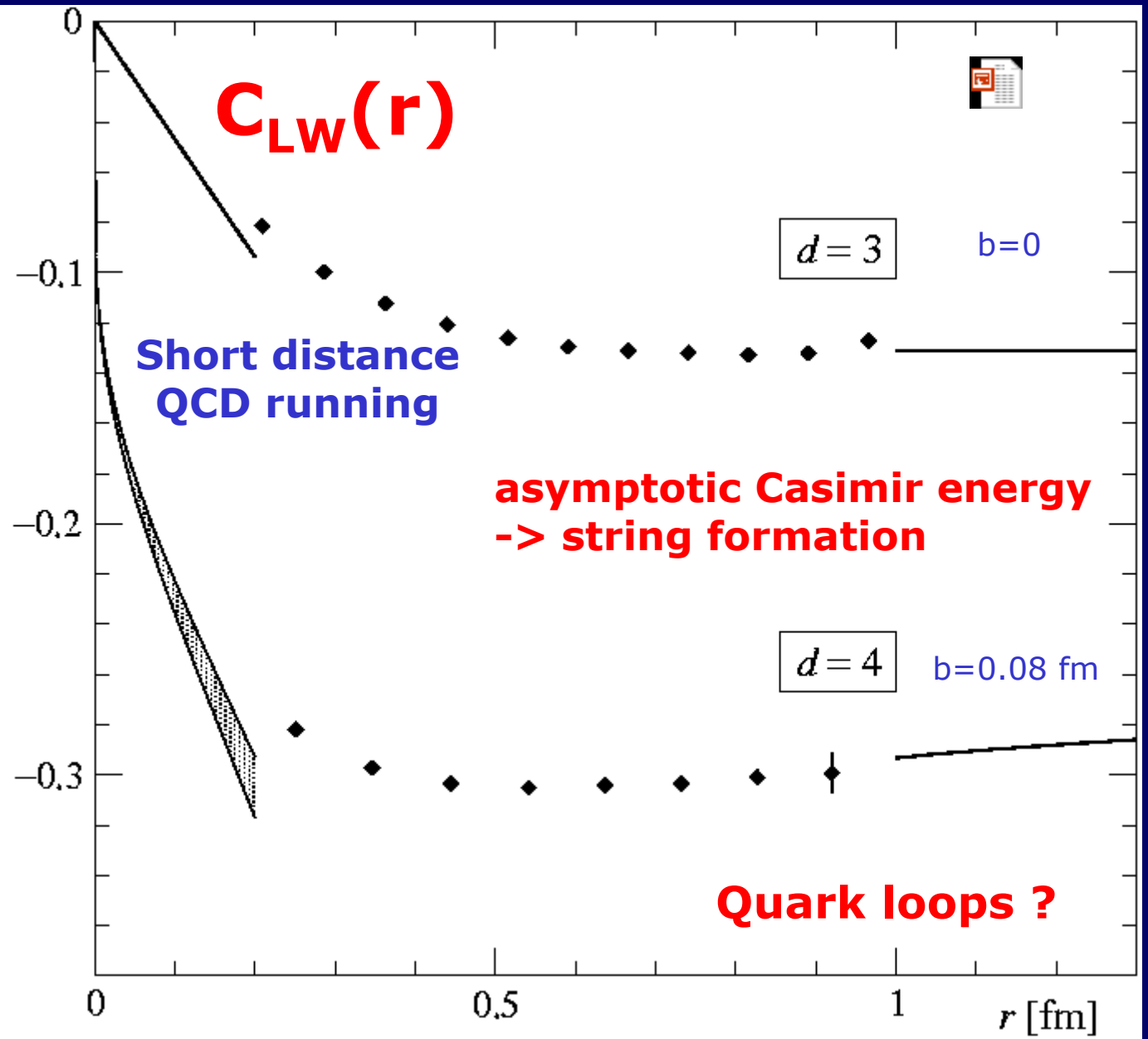






Luscher-Weisz Casimir Energy

SU(3)



$V(r) = \sigma r + \text{const} - \pi(d-2)/24r$

$F(r) = V'(r)$

$$C_{LW}(r) = \frac{1}{2} r^3 F'(r)$$

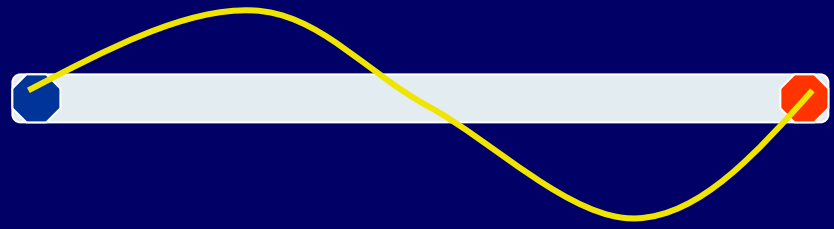
$-\pi(d-2)/24$

asymptotic r → infinity

Evidence for string formulation of QCD?

Loop equations
ADS string theory

$$S_{eff} = \frac{1}{2\pi\alpha'}\int_0^T d\tau \int_0^R d\sigma \left\{\frac{1}{2}\partial_a\xi\partial_a\xi + \cdots\right\}$$



Masless Goldstone field ⇔ collective string coordinate

Small wavelengths unstable!! => glueball emission

$$S_1 = \frac{1}{4}b\int_0^T d\tau \left\{(\partial_1\xi\partial_1\xi)_{\sigma=0} + (\partial_1\xi\partial_1\xi)_{\sigma=R}\right\}$$

Boundary operators

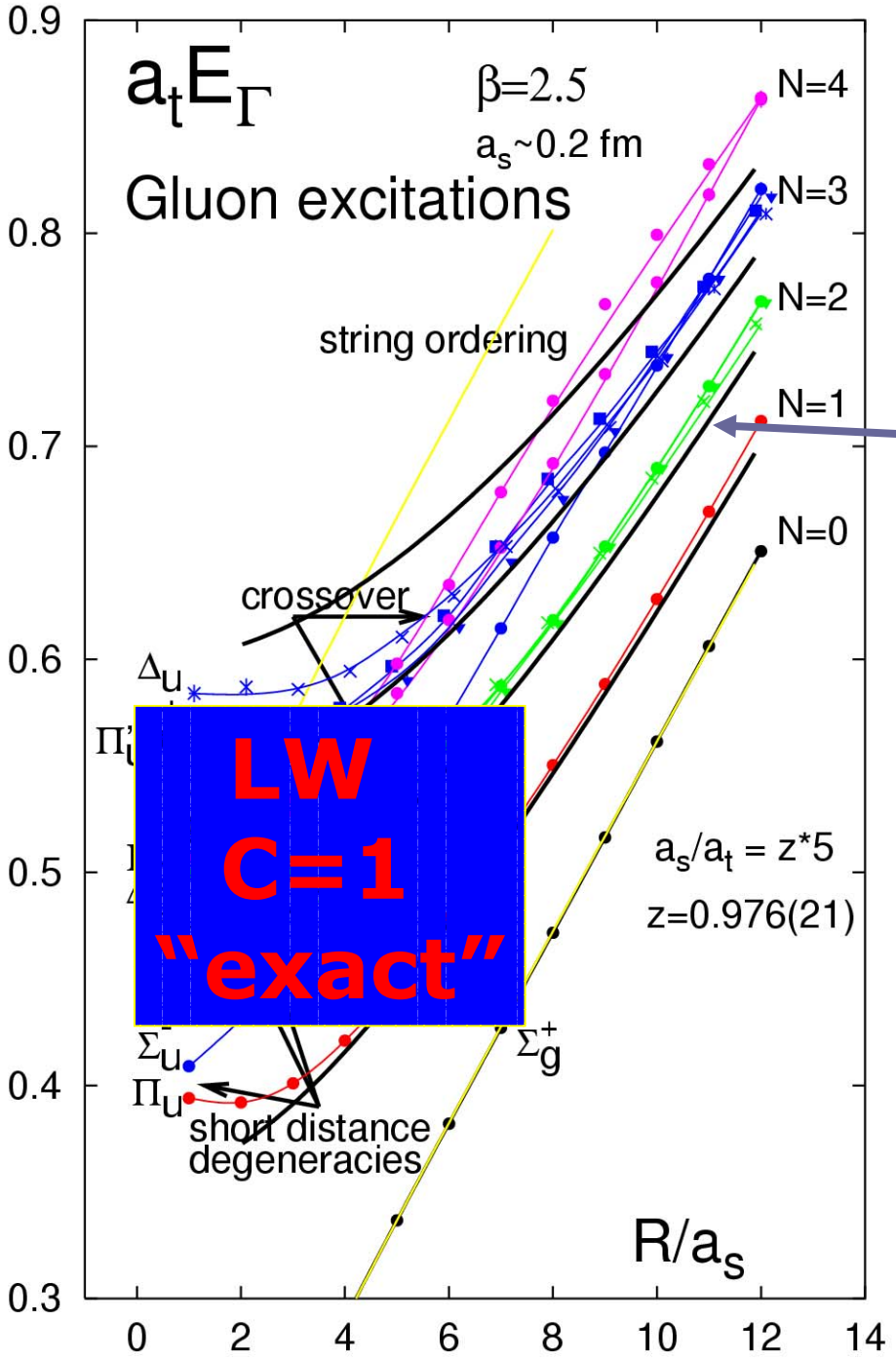
$$V(R) = \sigma R + \mu - \frac{\pi}{24R}(d-2)(1+\frac{b}{R})$$

$$\Delta E = \frac{\pi}{R}(1+\frac{b}{R})$$

$$S_2 = \frac{1}{4}c_2\int_0^T d\tau \int_0^R d\sigma \left\{\frac{1}{2}(\partial_a\xi\partial_a\xi)(\partial_b\xi\partial_b\xi)\right\}$$

Higher dimensional ops

$O(1/R^{3)}$



Fine structure in string formation

Nambu-Goto levels in black

Fine structure R~2-4 fm

Casimir energy puzzle:

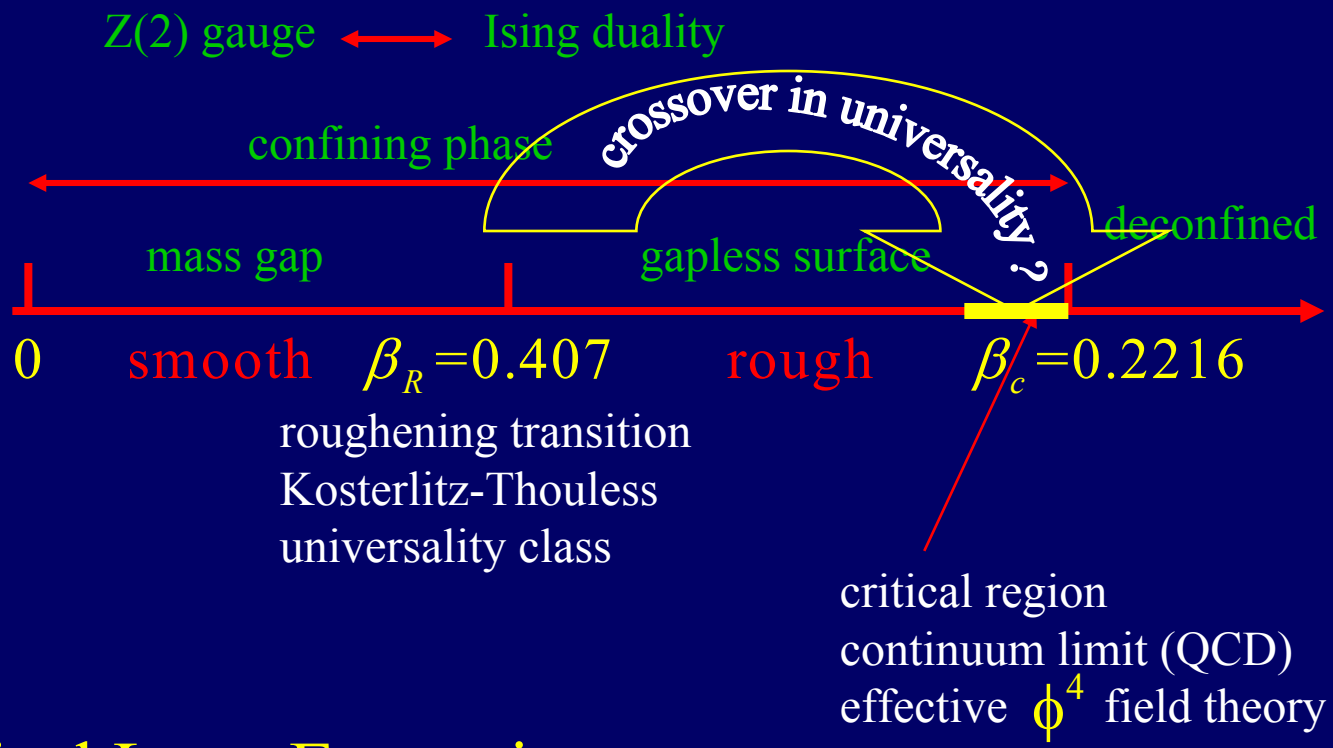
around R ~ 0.5 fm

1. Very few stable modes
2. Non string-like distortions

Wilson Surface of 3d Z(2) Gauge Model

Similar picture expected in QCD

$$\overline{\beta} = -\frac{1}{2}\ln(\tanh\beta)$$



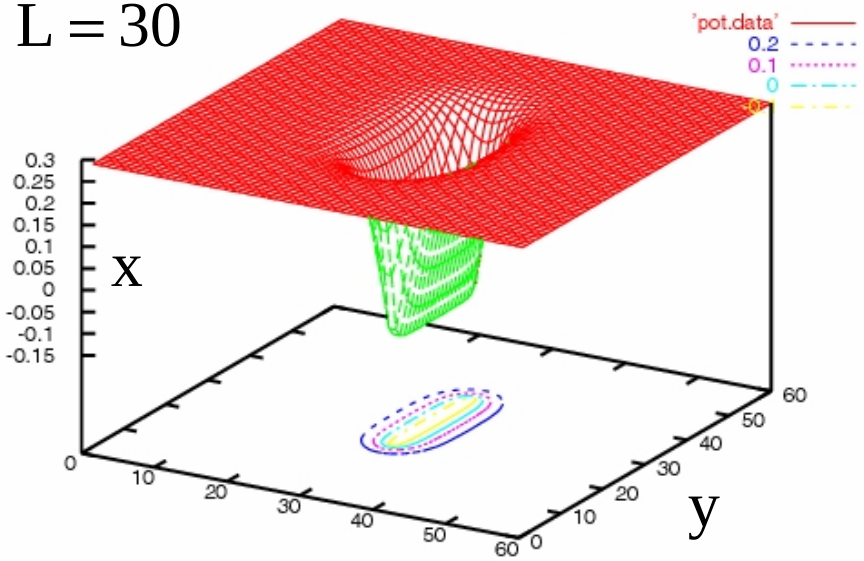
Semiclassical Loop Expansion

Soliton Quantization (string)

Effective Schrodinger equation
based on fluctuation matrix of string soliton

$$M = -\nabla^2 + U''(\phi_{soliton})$$

V_{eff}



- in long flux limit spectrum is expected to factorize

- translational zero mode of soliton

- Goldstone spectrum

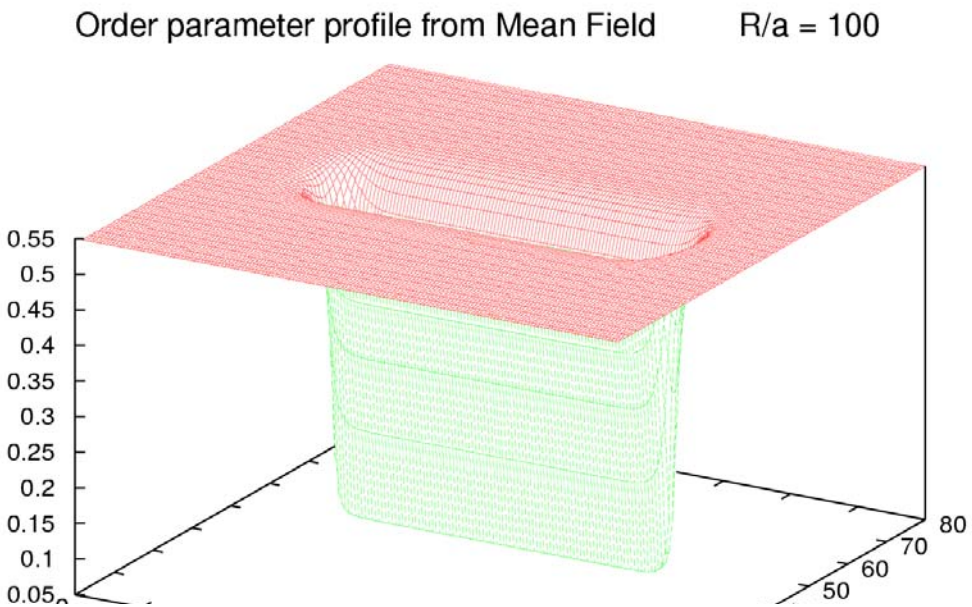
$$\phi(x)\cdot\exp(iqy)$$

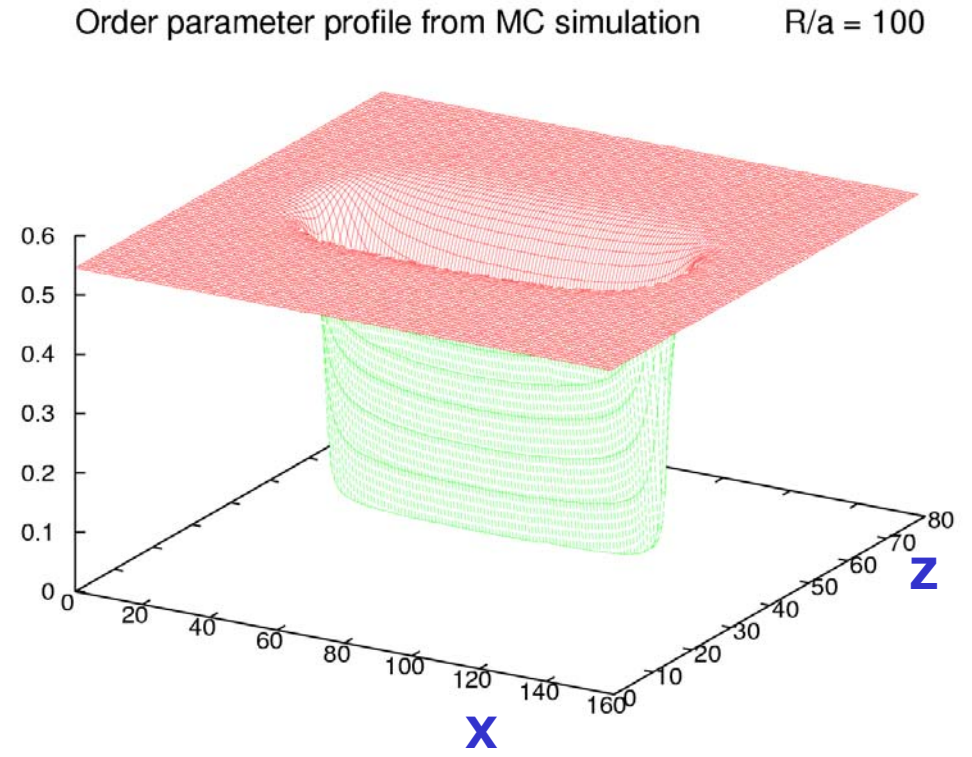
zero energy bound state

quantized momenta of Goldstone modes in box of length L

$$q = \frac{\pi}{L} n, \quad n = 1, 2, 3...$$

shape and end effects distort!





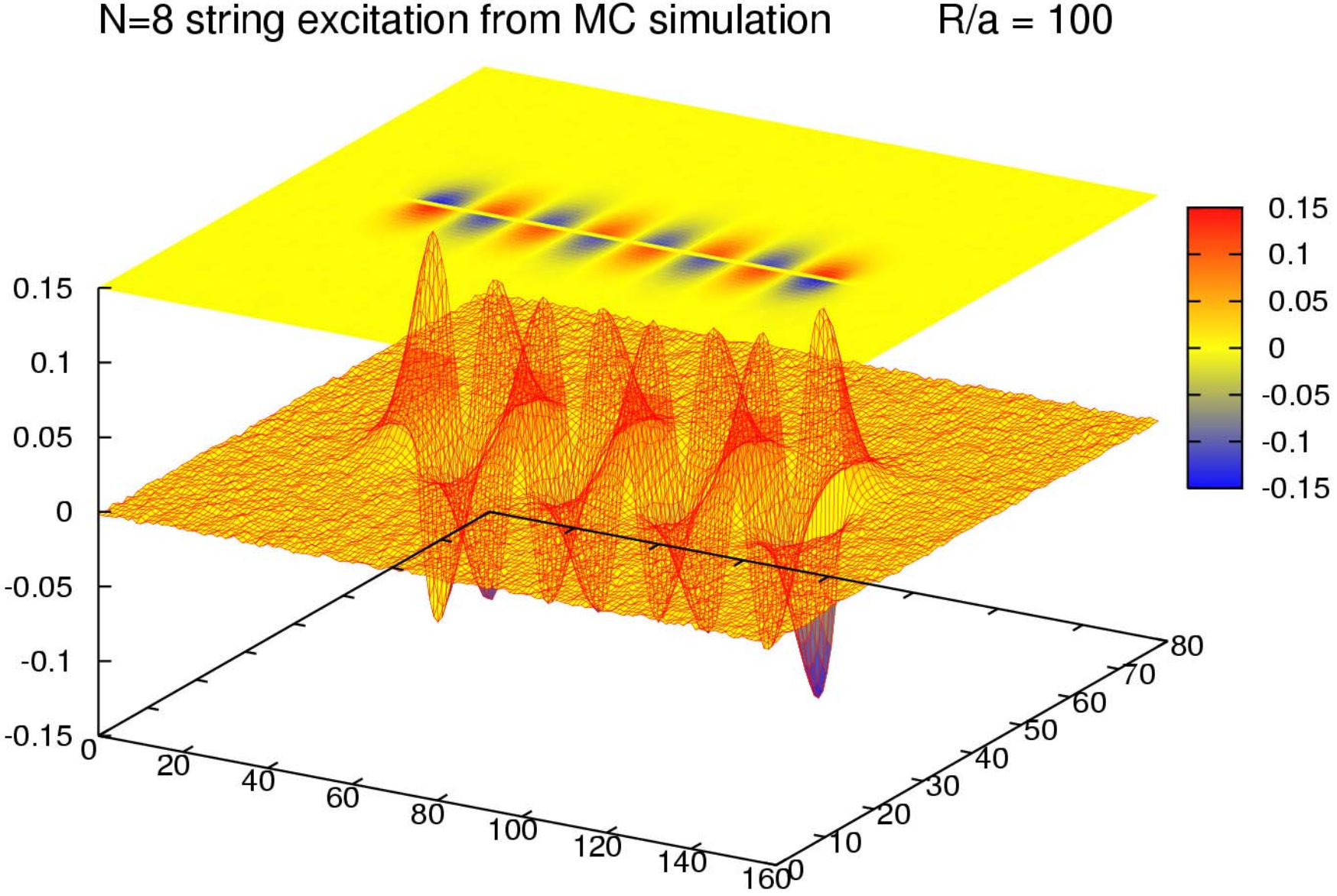
good analytic/numerical handle on the Z(2) model

in addition to MC

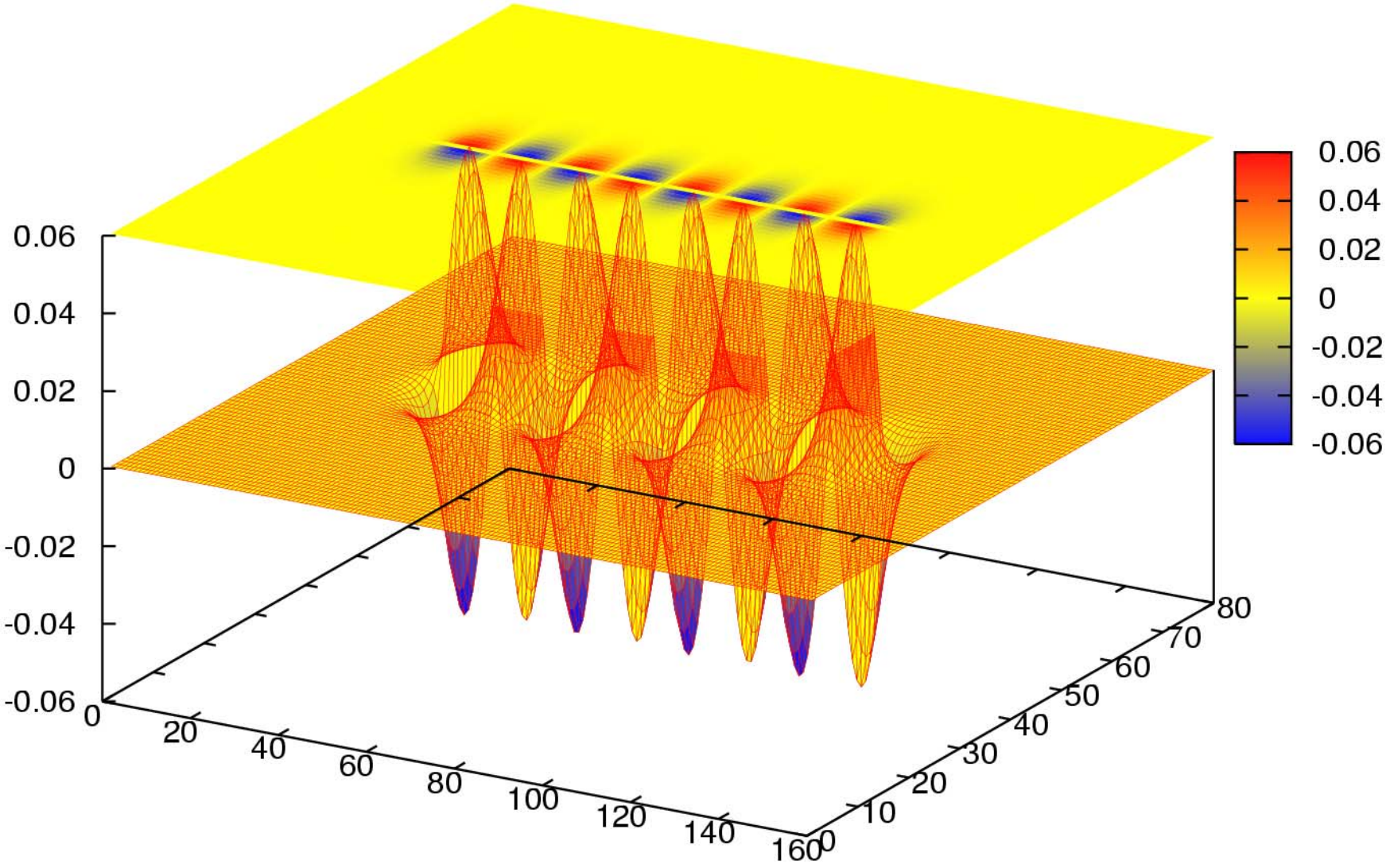
Effective Schrodinger potential

$P_x = +-1$ and $P_z = +-1$

two symmetry quantum numbers


N=8 string excitation from MC simulation
R/a = 100
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0
20
40
60
80
100
120
140
160
0
10
20
30
40
50
60
70
80

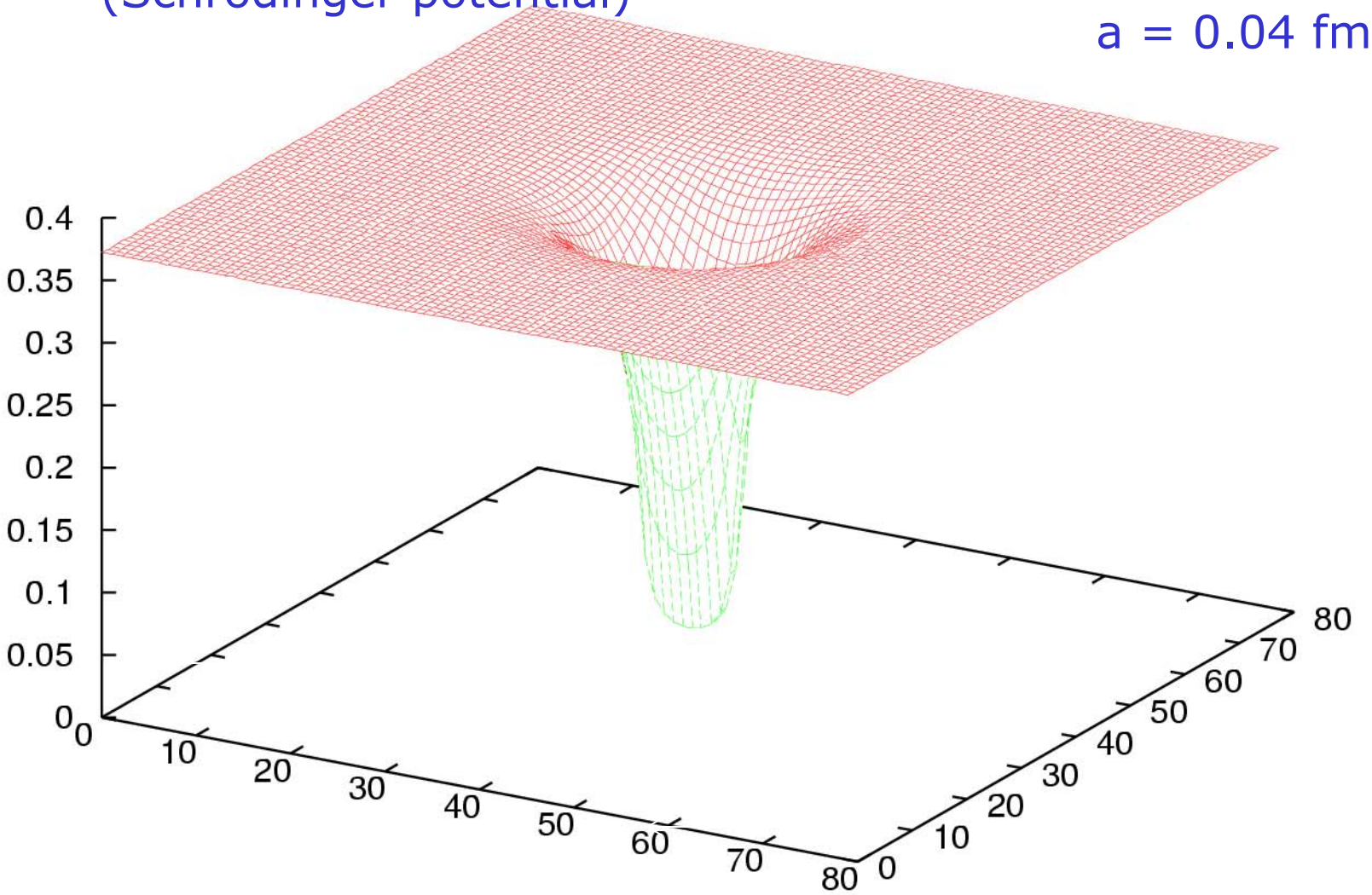
Analytic (from soliton quantization)



Order parameter profile from MC simulation R/a = 10

(Schrodinger potential)

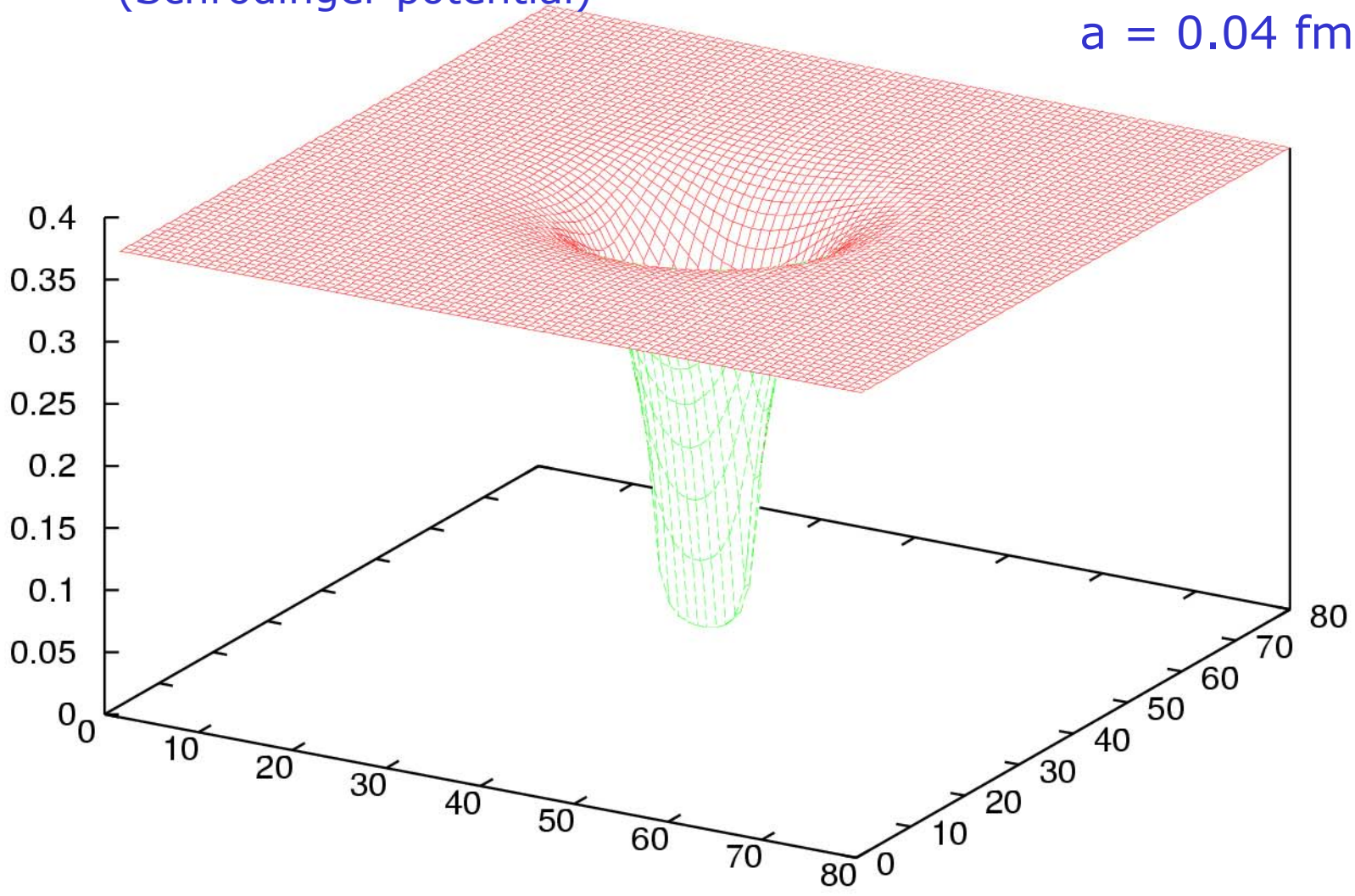
a = 0.04 fm

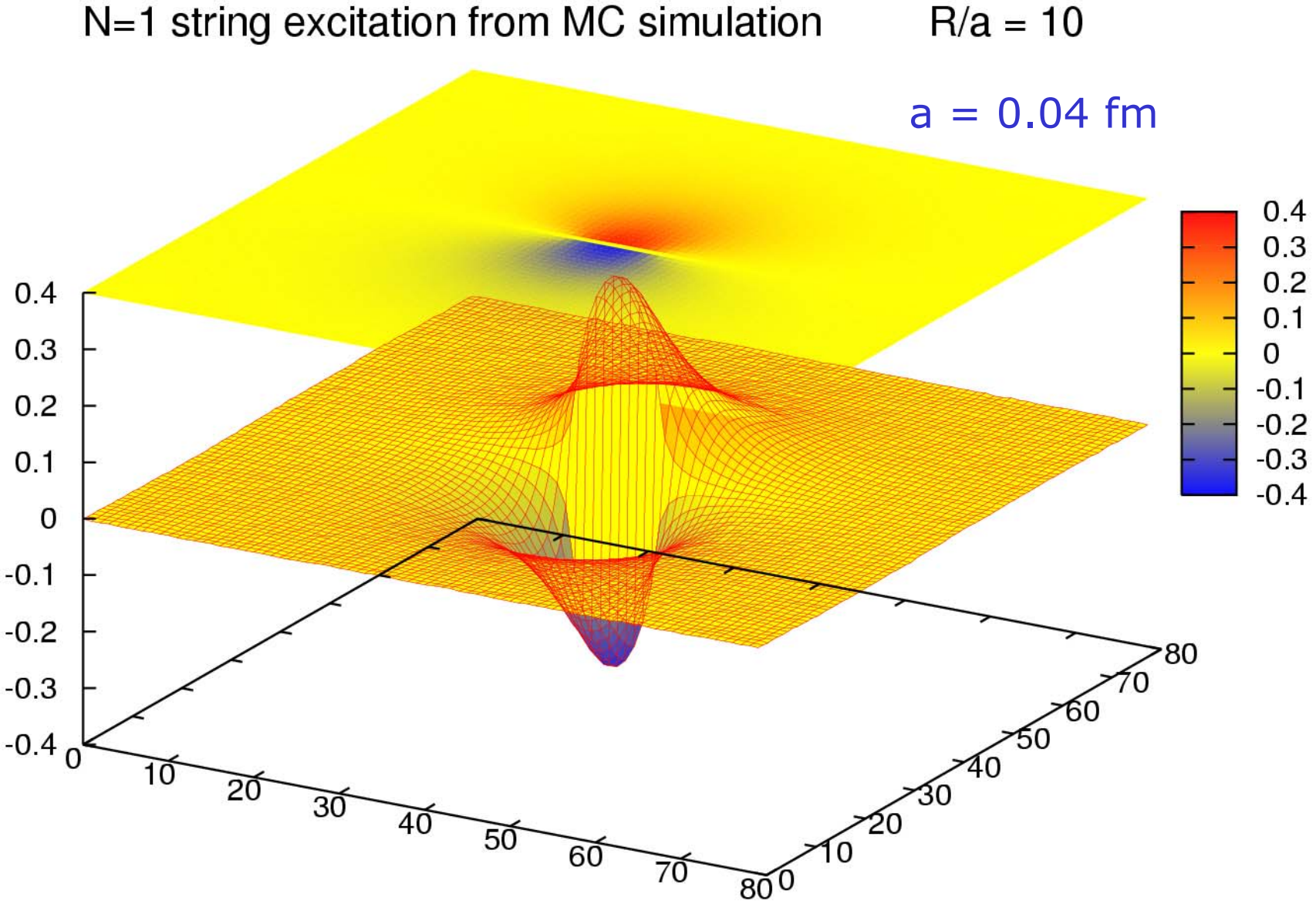


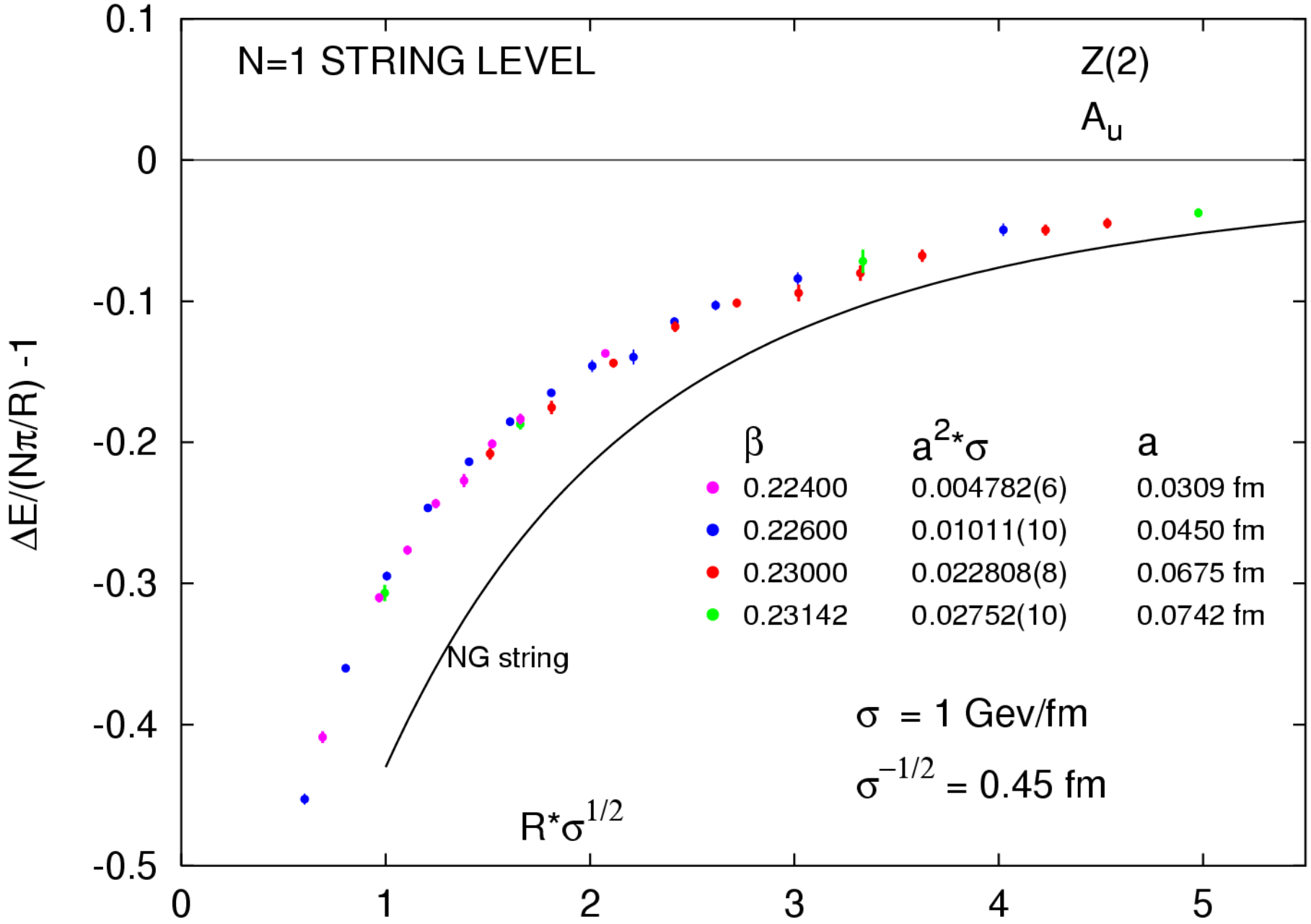
Order parameter profile from Mean Field R/a = 10

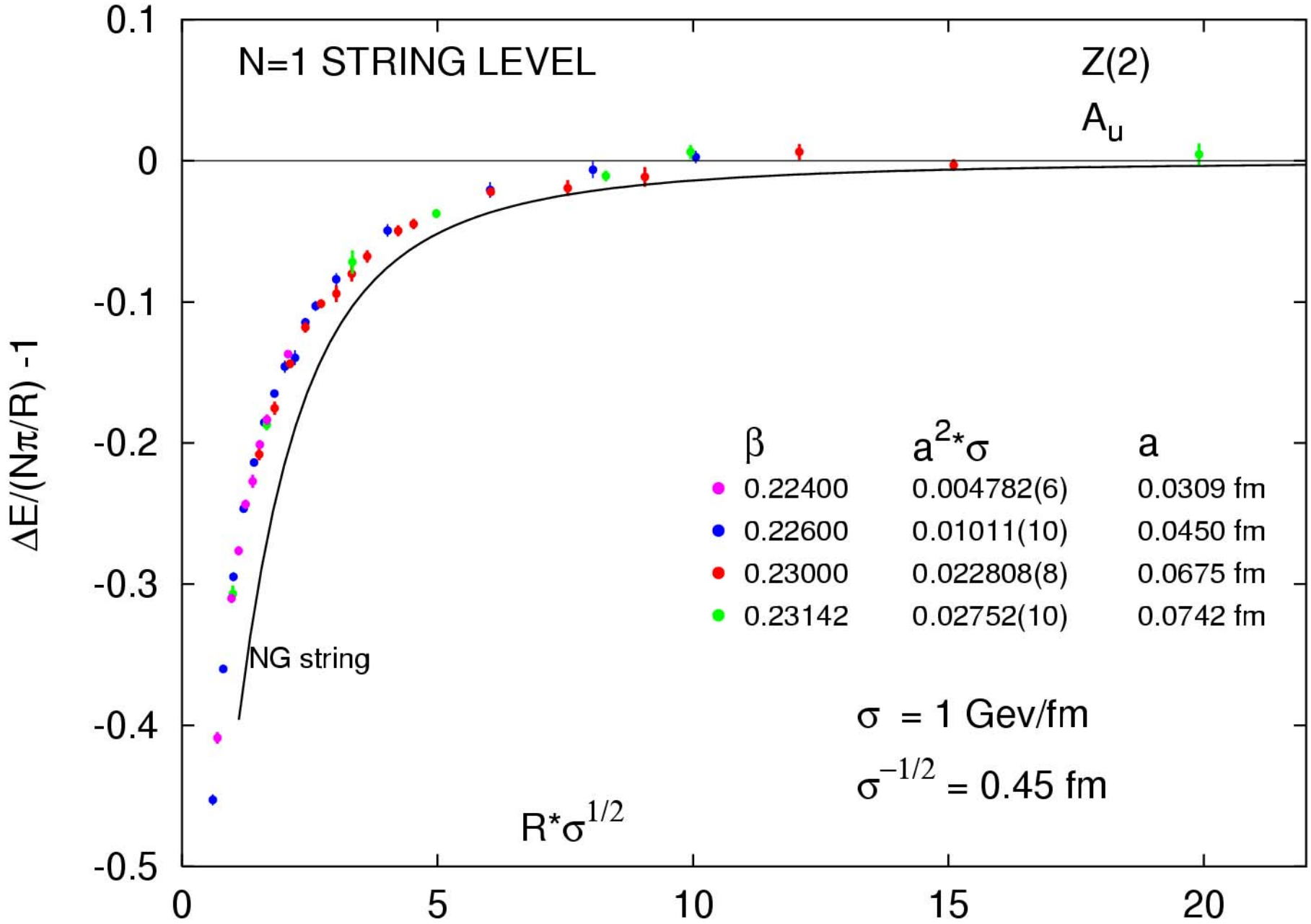
(Schrodinger potential)

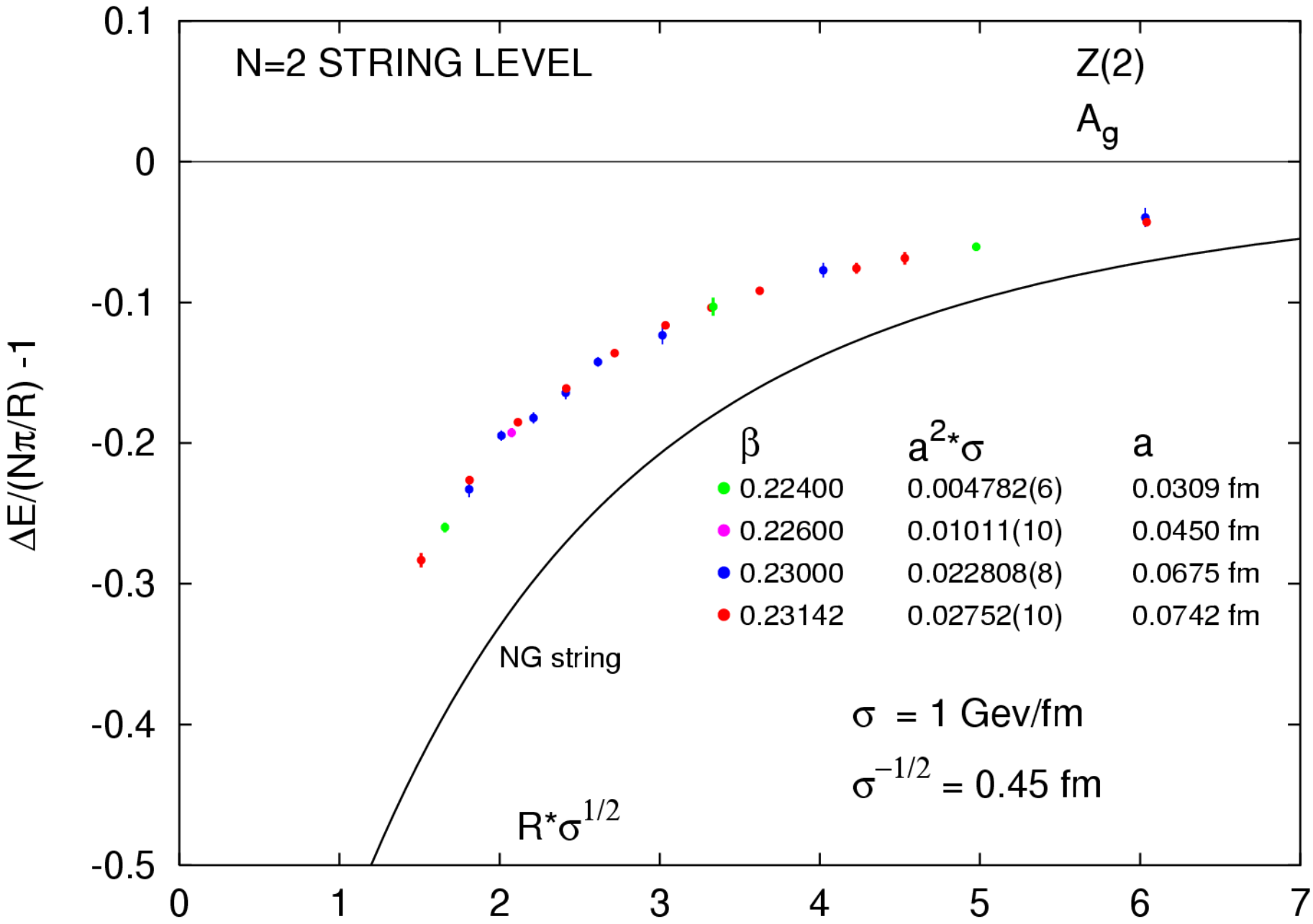
a = 0.04 fm

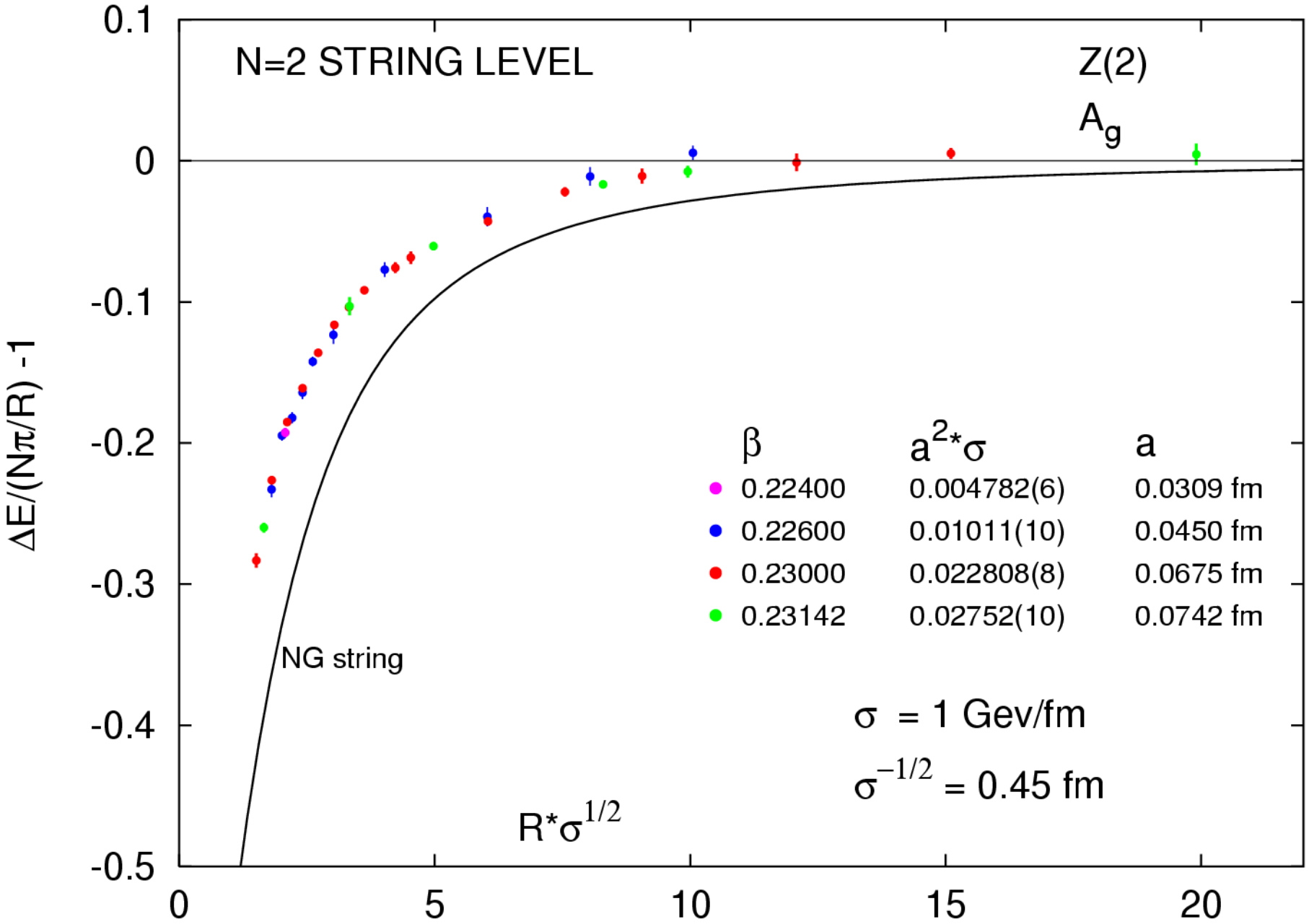


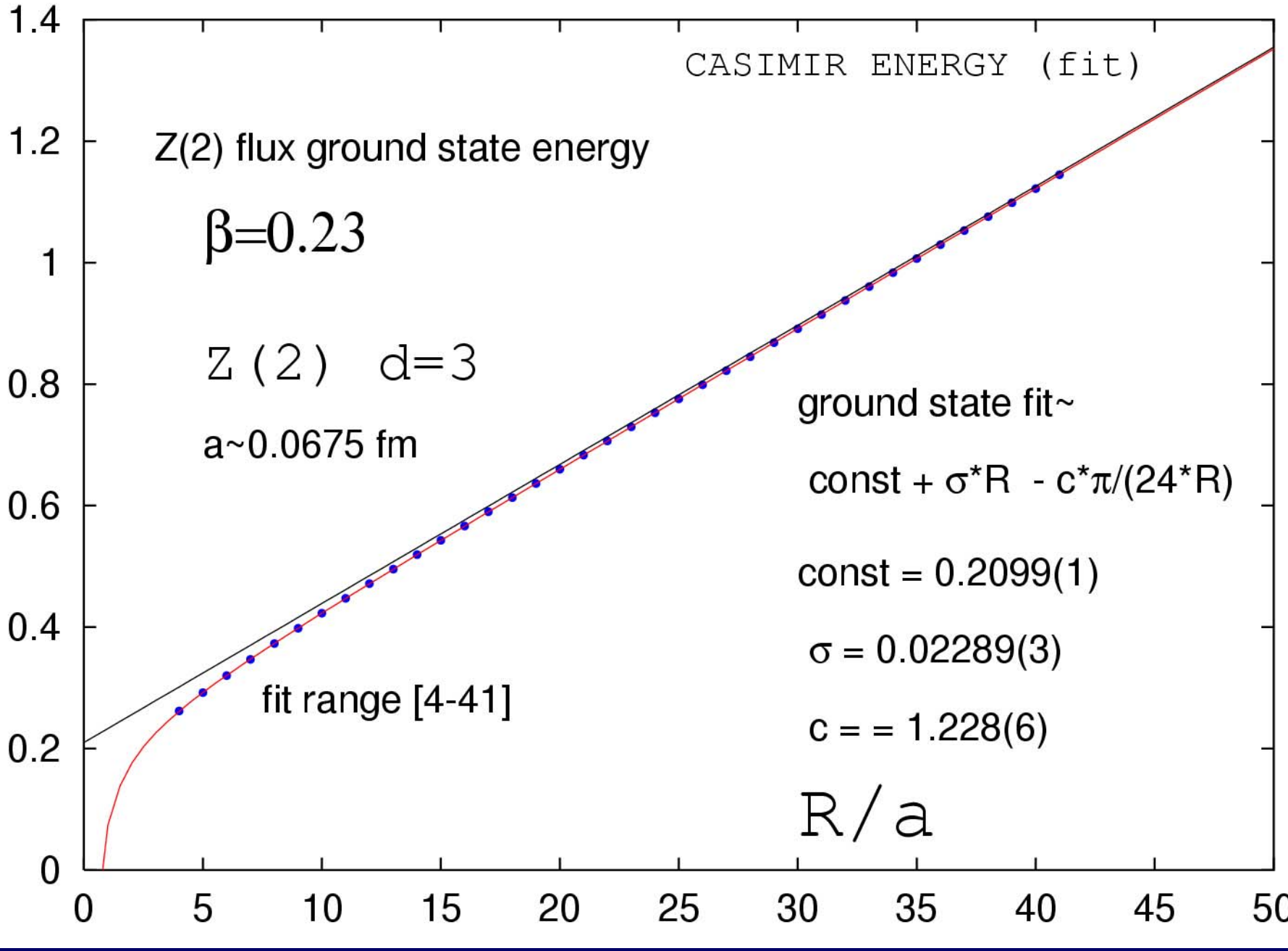

N=1 string excitation from MC simulation
R/a = 10
a = 0.04 fm
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0
10
20
30
40
50
60
70
80


N=1 STRING LEVEL
Z(2)
A_u
$\Delta E/(N\pi/R) - 1$
$R^*\sigma^{1/2}$
NG string
β
$a^2*\sigma$
a
0.22400
0.004782(6)
0.0309 fm
0.22600
0.01011(10)
0.0450 fm
0.23000
0.022808(8)
0.0675 fm
0.23142
0.02752(10)
0.0742 fm
σ = 1 Gev/fm
$\sigma^{-1/2}$ = 0.45 fm
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
5

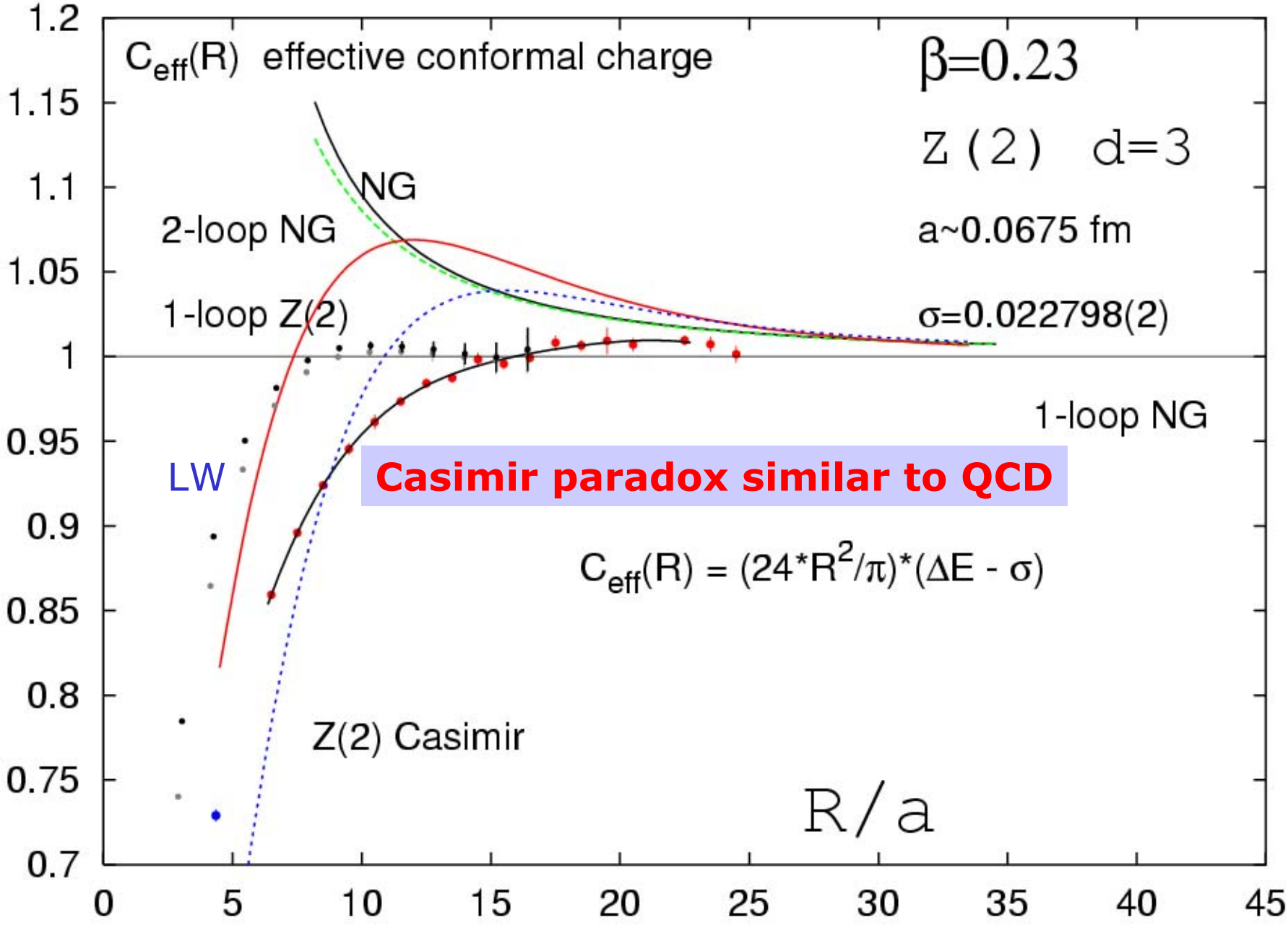

N=1 STRING LEVEL
Z(2)
A_u
$\Delta E/(N\pi/R) - 1$
$R^*\sigma^{1/2}$
NG string
β $a^{2*}\sigma$ a
0.22400 0.004782(6) 0.0309 fm
0.22600 0.01011(10) 0.0450 fm
0.23000 0.022808(8) 0.0675 fm
0.23142 0.02752(10) 0.0742 fm
σ = 1 Gev/fm
$\sigma^{-1/2}$ = 0.45 fm
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
5
10
15
20


N=2 STRING LEVEL
Z(2)
A_g
$\Delta E/(N\pi/R) - 1$
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
5
6
7
β
$a^2*\sigma$
a
0.22400
0.004782(6)
0.0309 fm
0.22600
0.01011(10)
0.0450 fm
0.23000
0.022808(8)
0.0675 fm
0.23142
0.02752(10)
0.0742 fm
NG string
σ = 1 Gev/fm
$\sigma^{-1/2}$ = 0.45 fm
$R*\sigma^{1/2}$

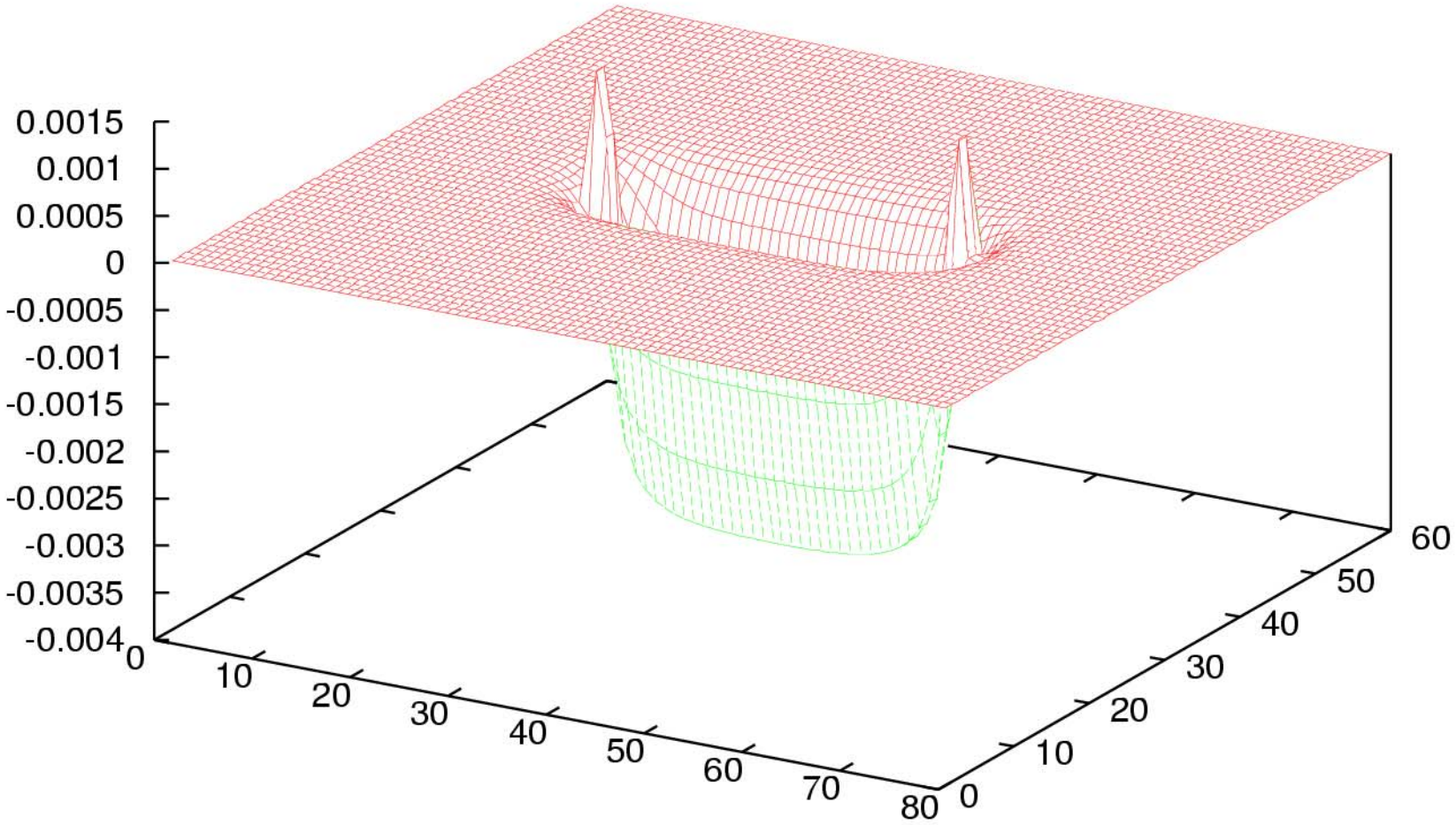

N=2 STRING LEVEL
Z(2)
A_g
$\Delta E/(N\pi/R) - 1$
$R^*\sigma^{1/2}$
NG string
β
$a^{2*}\sigma$
a
0.22400
0.004782(6)
0.0309 fm
0.22600
0.01011(10)
0.0450 fm
0.23000
0.022808(8)
0.0675 fm
0.23142
0.02752(10)
0.0742 fm
σ = 1 Gev/fm
$\sigma^{-1/2}$ = 0.45 fm
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
5
10
15
20

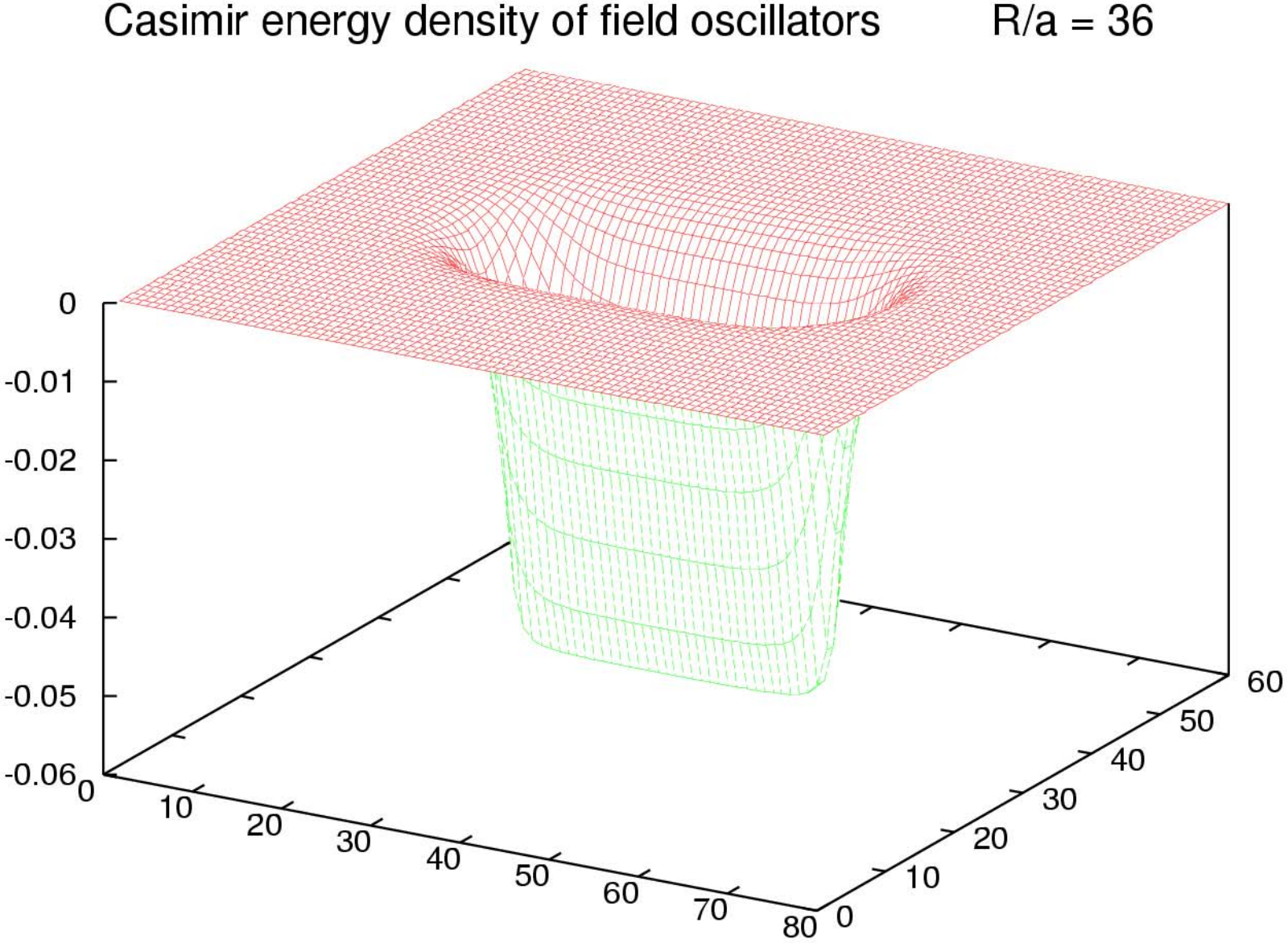

CASIMIR ENERGY (fit)
Z(2) flux ground state energy
β=0.23
Z(2) d=3
a~0.0675 fm
ground state fit~
const + σ*R - c*π/(24*R)
const = 0.2099(1)
σ = 0.02289(3)
c = = 1.228(6)
fit range [4-41]
R/a
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
40
45
50

Z(2) Casimir story

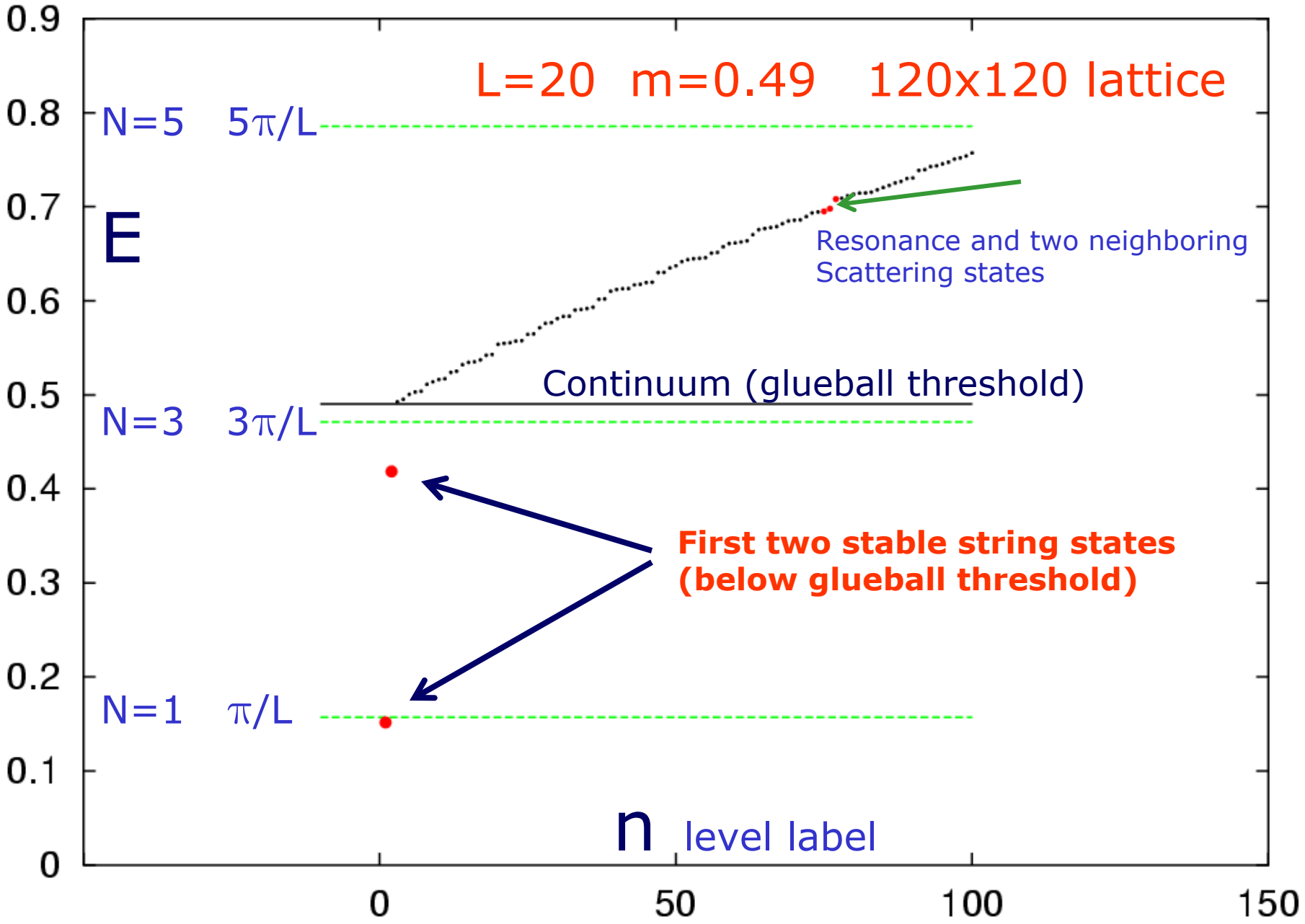


Casimir energy density R/a = 36

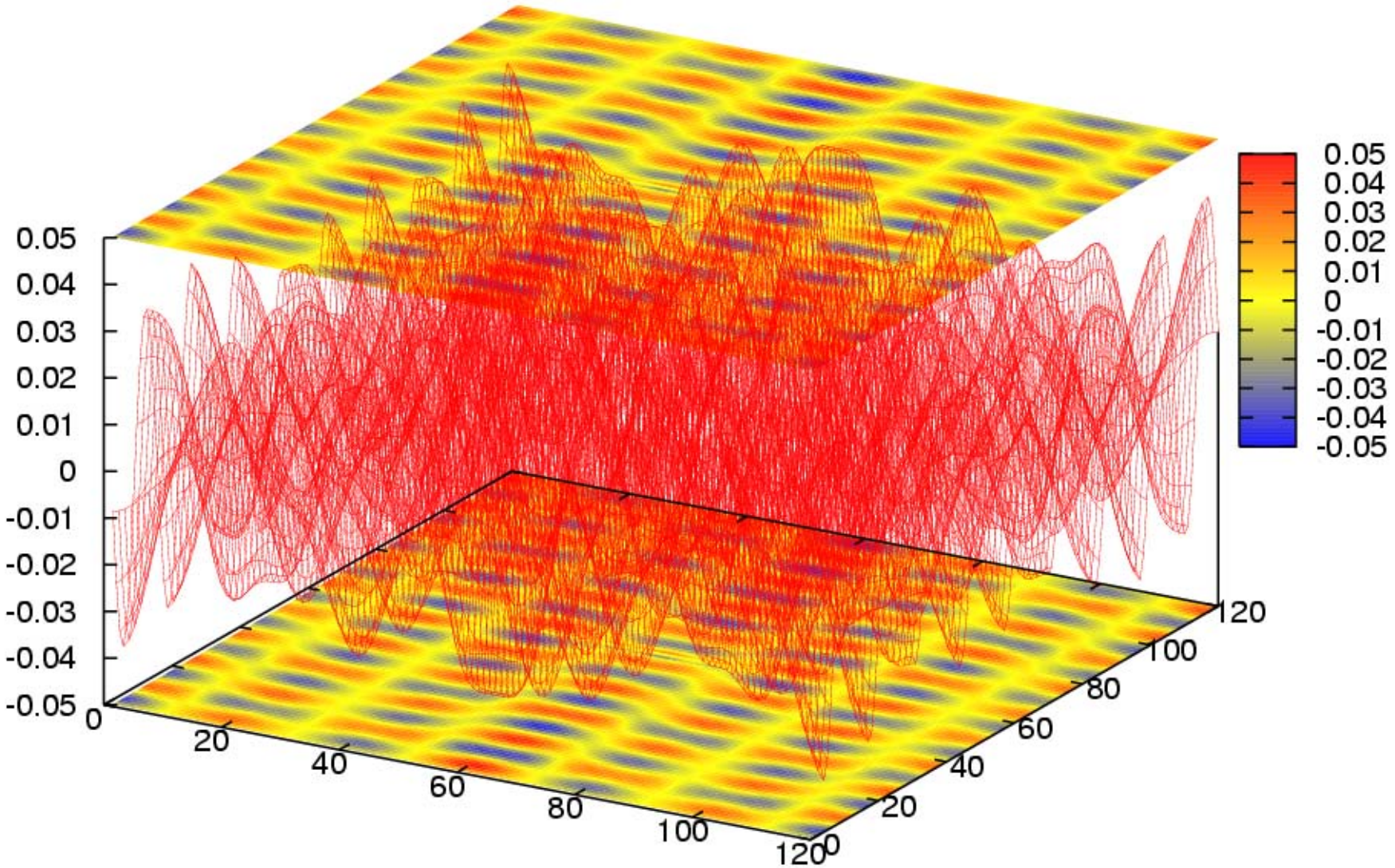



Casimir energy density of field oscillators
R/a = 36
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
0
10
20
30
40
50
60
70
80
0
10
20
30
40
50
60

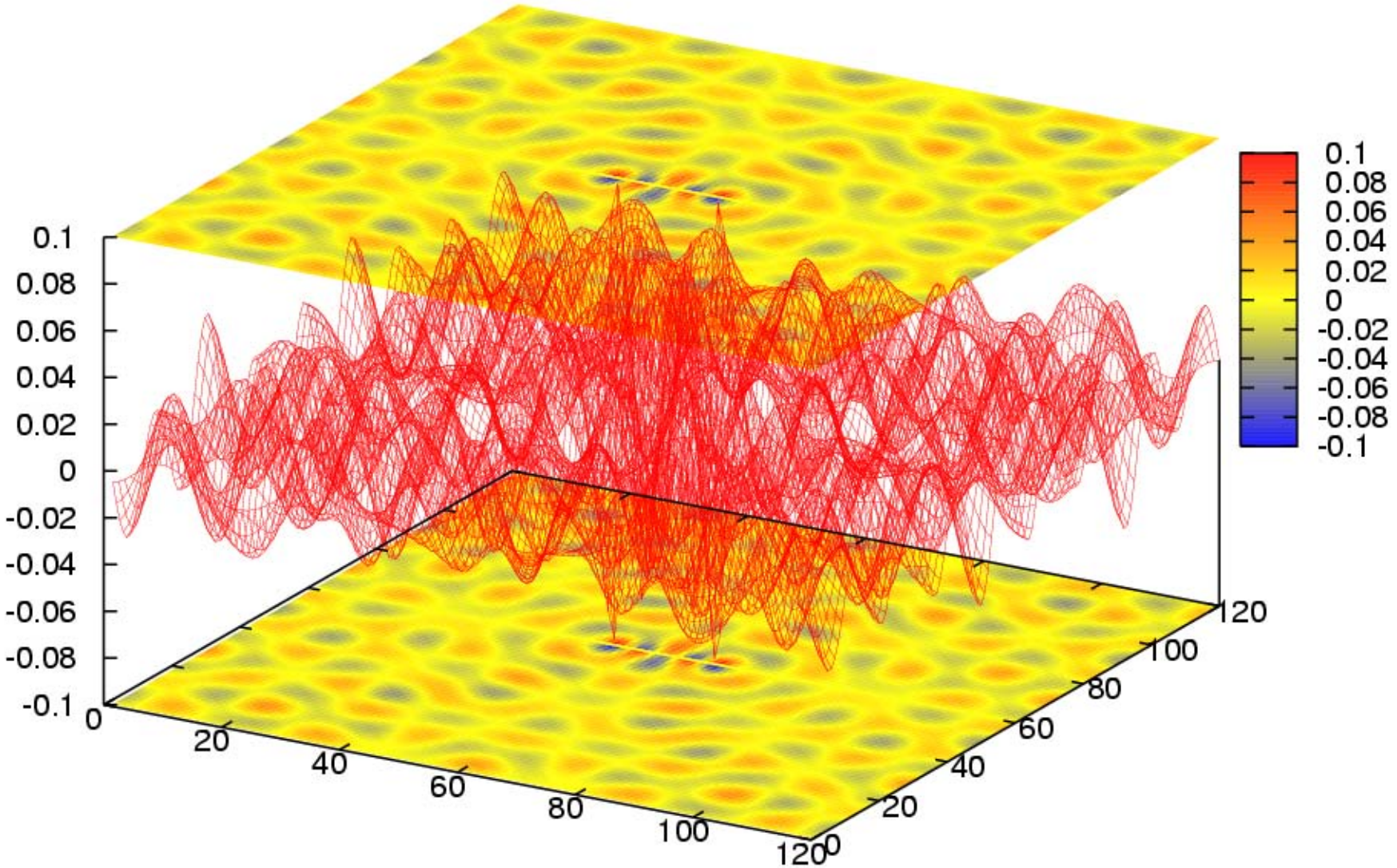
First 100 energy levels in (P_x=+1 P_z=-1) sector



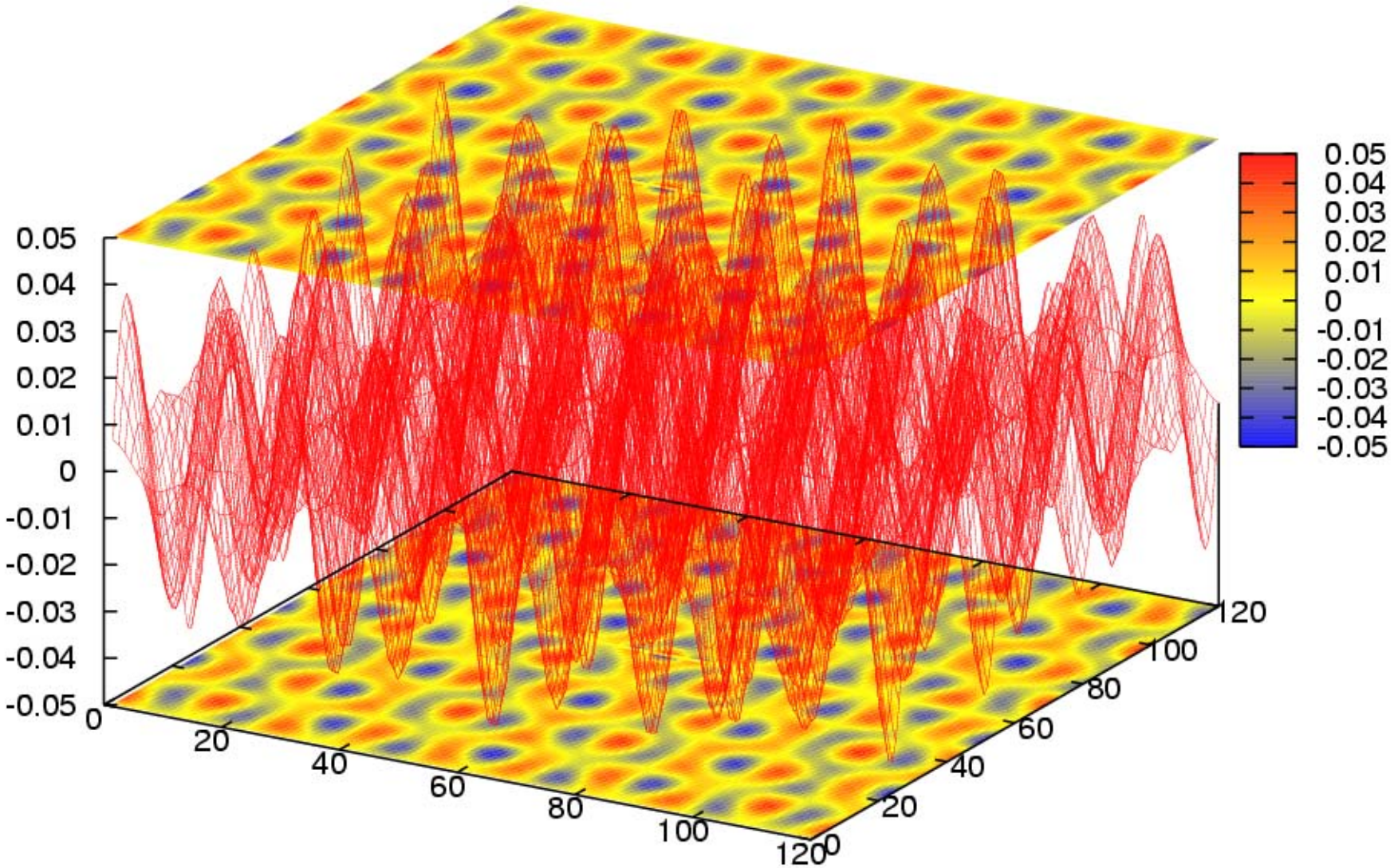
n=75 ordinary scattering state

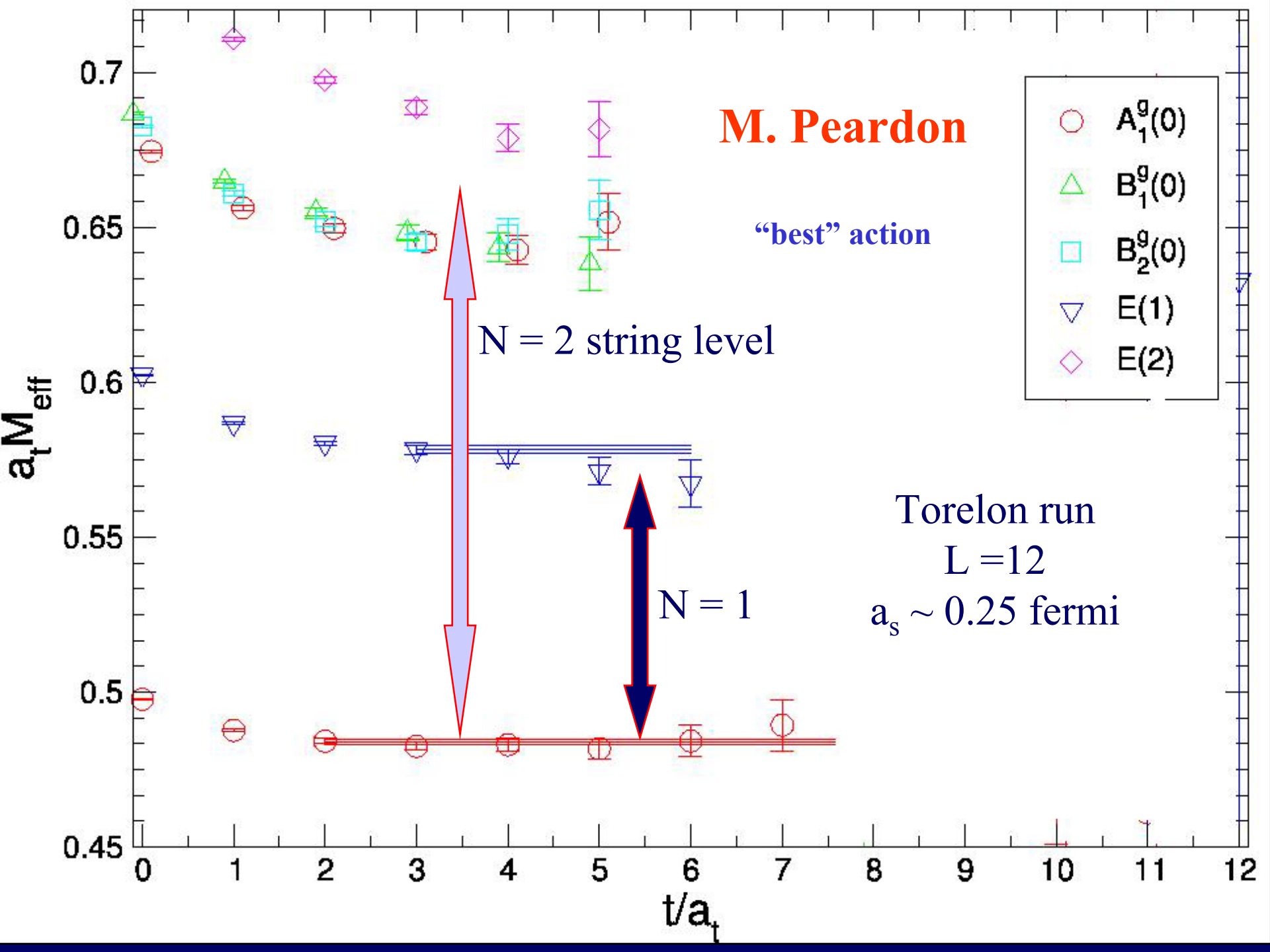


N=5 resonant string state n=76 energy level



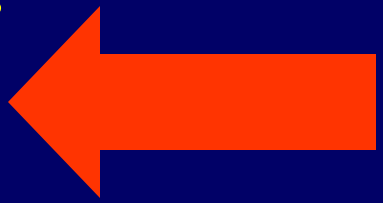
n=77 ordinary scattering state




M. Peardon
"best" action
N = 2 string level
N = 1
Torelon run
L =12
$a_s \sim 0.25$ fermi
$A_1^g(0)$
$B_1^g(0)$
$B_2^g(0)$
E(1)
E(2)
$a_t M_{eff}$
t/a_t
0.7
0.65
0.6
0.55
0.5
0.45
0
1
2
3
4
5
6
7
8
9
10
11
12

Conclusions on QCD String Spectrum:

1. Formation of some bosonic QCD string
2. Fine structure in the string spectrum



neither was seen before

3. Precocious onset of Casimir energy
4. Is the resonance spectrum the clue?
5. Progress on torelon spectrum Peardon
6. Effective low-energy string theory?
   Universality class of QCD string ?