Chiral Symmetry Breaking and Linear Confinement In Holographic QCD

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Based on the work with Prof. Mei Huang and Prof.Qi-Shu Yan

Talk Plan

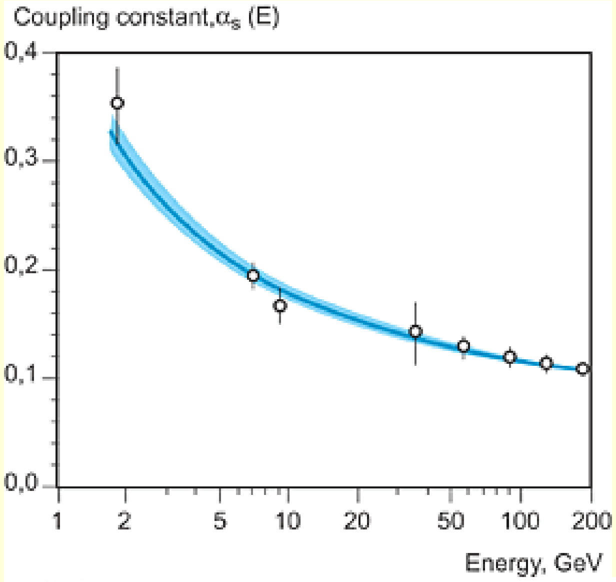
- A Brief Introduction to the Basis of Holographic QCD---AdS/CFT Correspondence
- Some realistic HQCD Models
- Incorperating Chiral Symmetry Breaking and Linear Confinement in a Unique Model
- Conclusion and Discussion

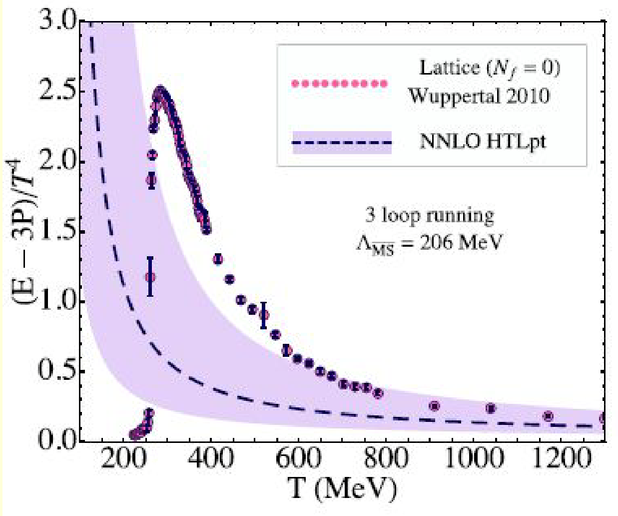
Strong Coupling Problem

When the coupling constant becomes large, the perturbative calculation in QCD becomes invalid due to the increasing effect of non-perturbative ingredients(magnetic monopole, vacuum condensate, soliton…).

Non-perturbative methods: Lattice simulation, DSE, Effective field theory…

Holographic QCD method



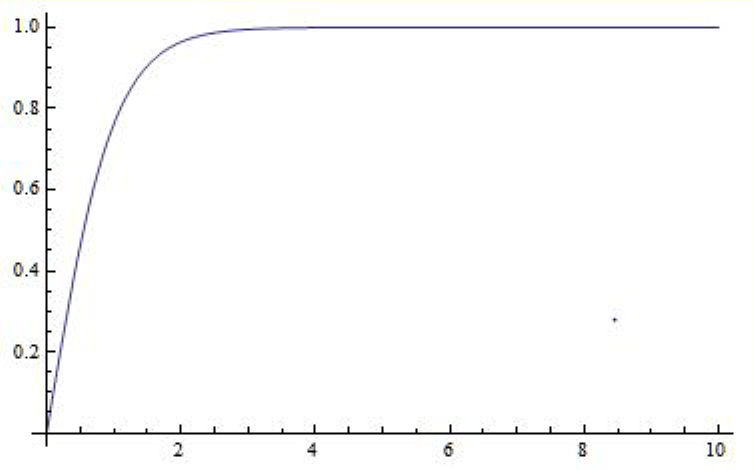


Andersen, Strickland and Su, JHEP 1008, 113 (2010)

From Background Expansion

When the gauge coupling become larger and larger, the perturbation theory become more and more invalid, which is considered as the involvement of non-perturbative degrees of freedom.

$$\mathrm{Tanh}(x) = 1 - 2e^{-x} + 2e^{-2x} + o(e^{-3x}), x \to \infty$$



$$\mathrm{Tanh}(x) = x - x^3 + o(x^4), x \to 0$$

Start from the expansion from 0 is hard to probe the property of large x.

An exact solution is almost impossible, the analytic tools depend on some kinds of expansion always. The AdS/CFT tells us it's possible to find the expansion on some background from a systematic approach.

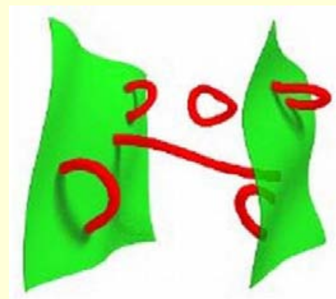
AdS/CFT Correspondence

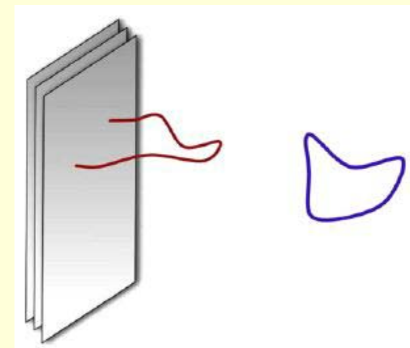
N D3-branes stack: open strings and closed strings

Low energy limit

SU(N) gauge field theory

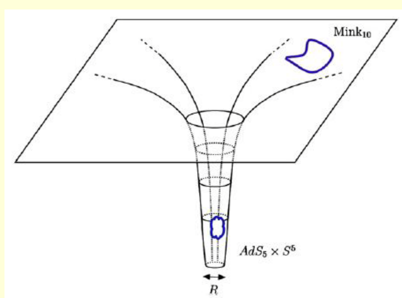
Theory in higher dimension gravity background

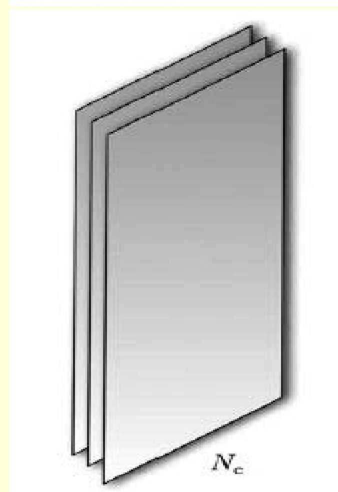




Strong coupling limit

Strong coupling limit





Theory in lower dimension flat background

Strongly coupled gauge theor

Curved space gravity solution for N D3-branes: Closed strings

Low energy limit

Closed string in AdS background

David Mateos, Class.Quant.Grav.24:S713-S740,2007

Strong-Weak Duality !

The condition we can trust the super gravity solution(AdS5):

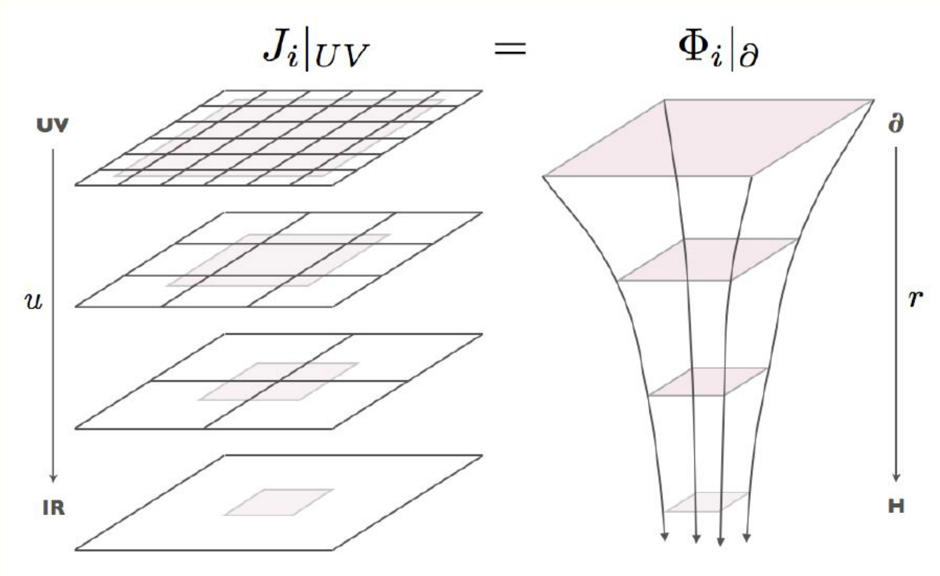
$$\frac{R^4}{l_s^4} = 4\pi g_s N_c >> 1$$

Which means, the t' Hooft Coupling of the YM theory are very large

$$\lambda = g_{YM}^2 N = 4\pi g_s N >> 1$$

Weak gravity, Strong Gauge

From Renormalization Group



The AdS/CFT tells us it's possible to encode the energy scale in a higher dimension, local, gravity theory. For example, the pure AdS5 geometric can be easily get from the following gravity system (a cosmology constant)

$$S = \frac{1}{16\pi G_5}\int d^5x\sqrt{-g}\,(R+\Lambda)$$

$$dS^2 = g_{mn}dx^m dx^n = \frac{L^2}{z^2}(dz^2 + \eta_{\mu\nu}dx^\mu dx^\nu)$$

The extra dimensions play the role of energy scale.

Adams, Carr, Schafer , Steinberg and Thomas, arXiv:1205.5180

The Equivalence of the Partition Function

The exact expression of the duality

$$< e^{\int \phi_0^i O_i} >_{CFT} = Z_{string}[\phi^i(x, z|_{boundary}) = \phi_0^i(x)]$$

since the gravity are weak, the saddle point approximation are adequate usually

$$Z_{string}[\phi^i] \approx e^{-I_{gravity}[\phi^i]}$$

Only need to solve some classical equation

Generalization: Gauge/Gravity Duality

Conformal Gravity Background: AdS Space

Dual

Conformal Field Theory: Super Yang Mills Theory

Widely Believed

$$S=\frac{1}{16\pi G_5}\int d^5x\sqrt{-g}\,(R+\Lambda)$$

Deformed the background geometric symmetry

Dilaton can break the conformal symmetry

Break the super symmetry and conformal symmetry

$$S_{GD}=\frac{1}{16\pi G_5}\int dx^5\sqrt{-g}\,e^{-2\phi}(R+4\partial_m\phi\partial^m\phi+V_s(\phi))$$

Non-Conformal Gravity Background

Dual

Gauge Field Theory with Scale

A conjecture

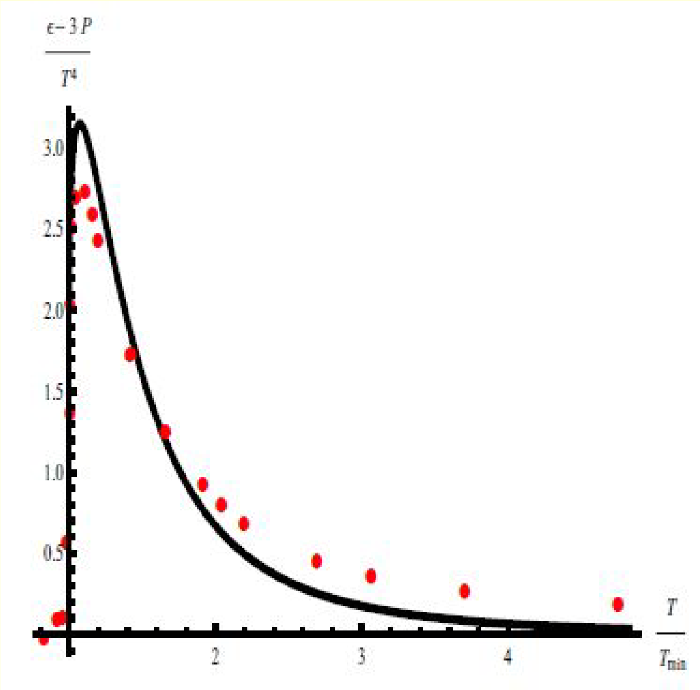
An application example

Though it's just a conjecture now, but many results show that it works very well in the strong coupling region.

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

The shear viscosity entropy density ratio bound

Kovtun,Son and Starinets, *Phys. Rev. Lett. 94 (2005) 111601*



It can depict the trace anormally peak near the Tc, which is much better than perturbation theory

D.Li,M.Huang, Q.S.Yan, JHEP(2011)041

Methods

Bottom-Up approach:

Start from the dynamics of the lower dimension strong coupled field theories, and try to find the dual gravity background phenomenologicaly

⇓

Construct some gravitybackground (by hand or by some lower dimension gravity theory), and consider the perturbation on it

Top-Down approach:

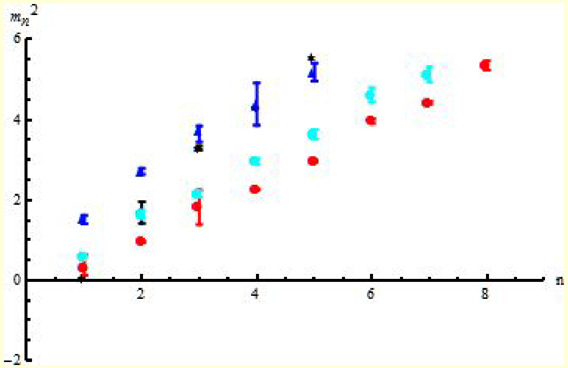
Start from string theory, try to break the symmetry and construct the non-conformal background.

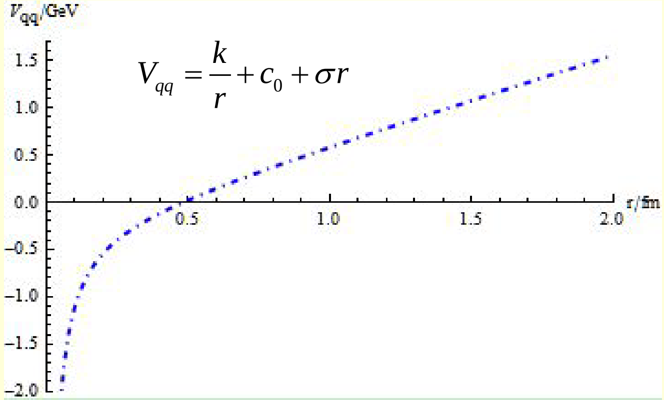
⇓

Perturbation on it, and get the correlation function

QCD Vacuum Properties

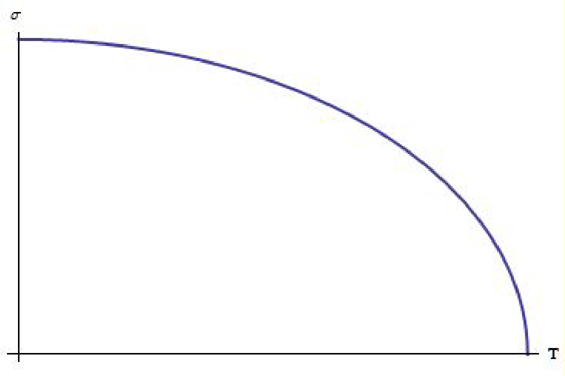
1. The mesons' spectra has a linear behavior, which is considered to be related to the linear potential of quark-antiquark. And reflect the confinement property of QCD





2. The chiral condensate break the chiral symmetry and produce mass splits of the chiral partners.

At lower T, quark and anti-quark can form a pair and behave like a boson, which can condensate. At higher T, the pair would be broken by thermal fluctuation and the condensate would disapear.

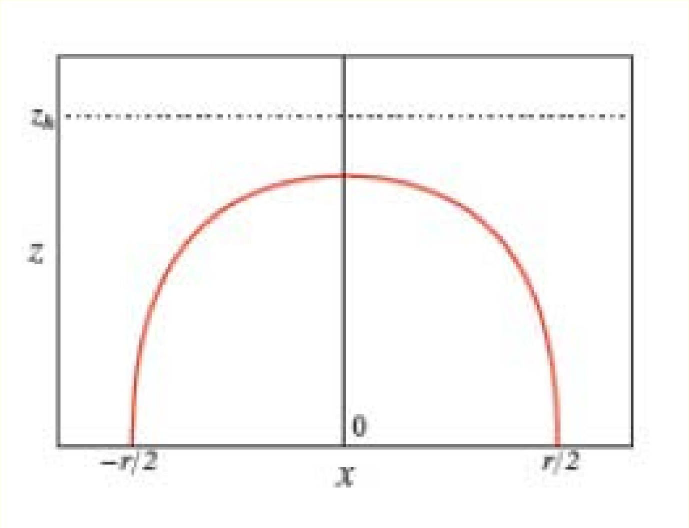


The quark-antiquark potential in Holographic QCD

In holographic QCD, the quark-antiquark potential are calculated by minimizing the action of a effective string attaching to two quarks in the boundary and propagating in the gravity background.

J.M.Maldacena, hep-th/9803002

$$S_{NG} = \frac{1}{2\pi\alpha}\int d^2\eta\sqrt{Det\ \kappa_{ab}}$$



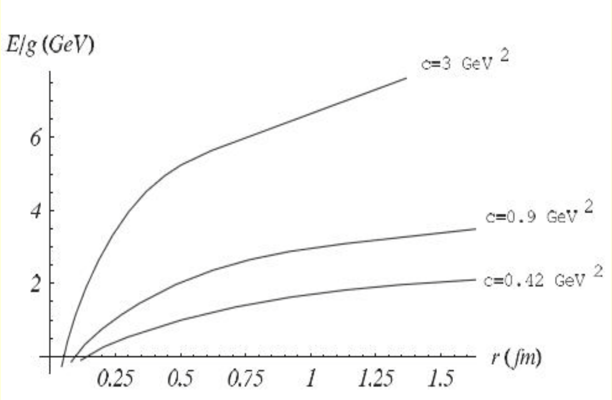
Linear Potential in HQCD

Andreev and Zakharov propose the following background metric,

$$dS^2 = g_{mn}dx^m dx^n = \frac{L^2 e^{\frac{1}{2}cz^2}}{z^2}(dz^2 + \eta_{\mu\nu}dx^\mu dx^\nu)$$

It deformed the warp factor

It shows such a system may correct reflect the gluon dynamics, since it reproduce the correct linear potential



O. Andreev, V.Zakharov, Phys.Rev.D74:025023,2006

However, such a background is inproper to get the correct meson spectra behavior

Chiral Symmetry Breaking and meson spectra in HQCD

Karch.et.al(2005) propose to consider the following 5D system with $SU(2)_L \times SU(2)_R$ symmetry:

Karch, Katz,Son,Stephonov, Phys.Rev.D74:015005,2006

$$S_{kkss} = \int dx^5 \sqrt{-g} e^{-\phi} [| DX |^2 + 3 | X |^2 - \frac{1}{4g_5^2} (F_L^2 + F_R^2)]$$

The metric is still conformal AdS5:

$$dS^2 = g_{mn} dx^m dx^n = \frac{L^2}{z^2} (dz^2 + \eta_{\mu\nu} dx^\mu dx^\nu)$$

The introduce the dilaton field ϕ , and assuming it a quadratic profile to break the conformal symmetry

$$\phi = \mu^2 z^2$$

Chiral Symmetry Breaking in Softwall Model

Assuming the condensate of X: $X = \frac{\chi(z)}{2} I_2$

The equation of motion of χ

$$\chi'' - (\frac{3}{z} + 2z)\chi' + \frac{3}{z^2}\chi = 0$$

The asymptotic behavior of χ near the UV boundary(z=0) is

$$\chi = m_q z + \sigma z^3 + o(z^4)$$

σ is related to the chiral condensate, and χ can cause a split on the mass spectrum of vector and axial vector mesons

$$V_\rho = \frac{A_s'' - \phi''}{2} + \frac{(A_s' - \phi')^2}{4}$$

$$V_{a_1} = \frac{A_s'' - \phi''}{2} + \frac{(A_s' - \phi')^2}{4} + g_5^2 \chi^2 e^{2A_s}$$

Calculate the correlation function and the masses of mesons

Since the 5D theory should be weakly coupled, one can use the saddle point approximation, the partition function is related to the onshell action as following(take the vector part as an example):

$$Z = e^{-S_{onshell}} = e^{\frac{1}{2g_5^2}\int d^4x(\frac{1}{z}V_\mu^a \partial_z V^{\mu a})_{z=uvcut}} = < e^{\int d^4x V_{0,\mu} J^\mu} >$$

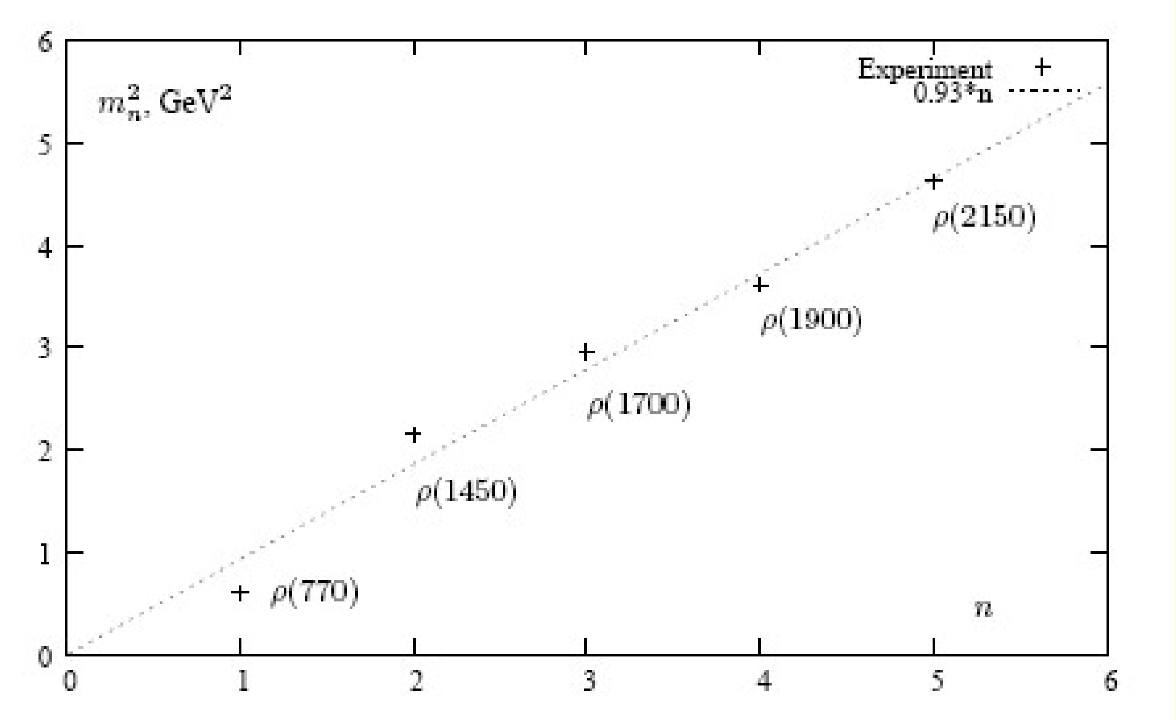
To calculate the correlation of the current $J_\mu^a = \bar{q}\gamma_\mu t^a q$

One can do fuctional derivative twice with respect to the boundary value of vector field $V_{0,\mu}^a$, with $V_\mu^a = V(q,z)V_{0,\mu}(q)$

In KKSS model, the vector mesons' masses can be seen from the peak of the correlation function (especially in finite temperature case), and present the linear behavior.

Regge behavior in KKSS Model

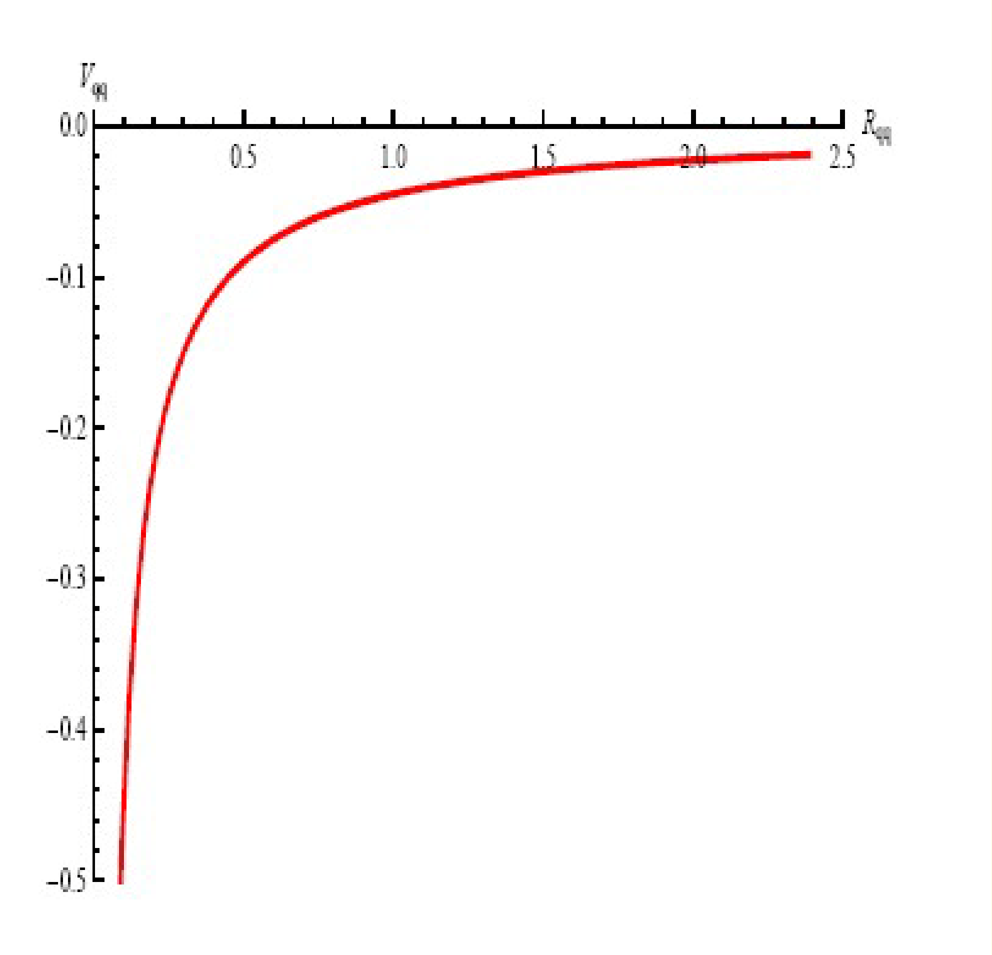
$$m_n^2 = 4\mu^2 n$$



Rho mesons' mass square V.S. radial excitation number n

The quark-antiquark potential in KKSS model

The pure AdS5 can't produce the linear potential. The KKSS model only produce the coulomb part.



To construct a self-consistent Dual Model

1. The input of the model should reflect the dynamics of the 4D field theory(such as vacuum condensate).

2. The gravity background should be modified by the 4D dynamics.

3. It should cover the linear spectra,the linear potential, the chiral symmetry breaking simultaneously.

Both the gravity background of the Andreev-Zakharov model and the KKSS model are input by hand. And none of them can incoperate the linear spectra, the linear spectrum and the chiral symmetry breaking.

The Graviton-Dilaton System

The coupling of the theory is related to the dilaton field. And since we are dealing with a non-conformal theory, the dilaton is no longer a constant; instead it dominates the effect in IR region. The metric should be deformed to match the dilaton profile. The simplest system to consider such an effect is the graviton-dilaton system:

$$S_{GD} = \frac{1}{2\kappa^2}\int dx^5 \sqrt{-g}\, e^{-2\phi}(R + 4\partial_m \phi \partial^m \phi + V_s(\phi))$$

And this system may reflect the pure gluon dynamics while the KKSS action may reflect the quark dynamics.

To cover the linear confinement and the chiral symmetry breaking

Adding the quark dynamics(combine the two model):

$$S_{GD} = S_{GD} + \frac{N_f}{N_c} S_{KKSS}$$

Field Contents $\quad X = (\frac{\chi}{2} + s)e^{i2\pi^a t^a}; A_\mu; V_\mu$

Metric Ansatz $\quad dS^2 = e^{2A_s(z)}(-dt^2 + dz^2 + dx_i dx^i)$

ϕ profile Ansatz $\quad \phi = \mu^2 z^2$

χ profile Ansatz $\quad \chi = m_q z + \sigma z^3 + o(z^4)$

Equation of Motion

Background field Equation

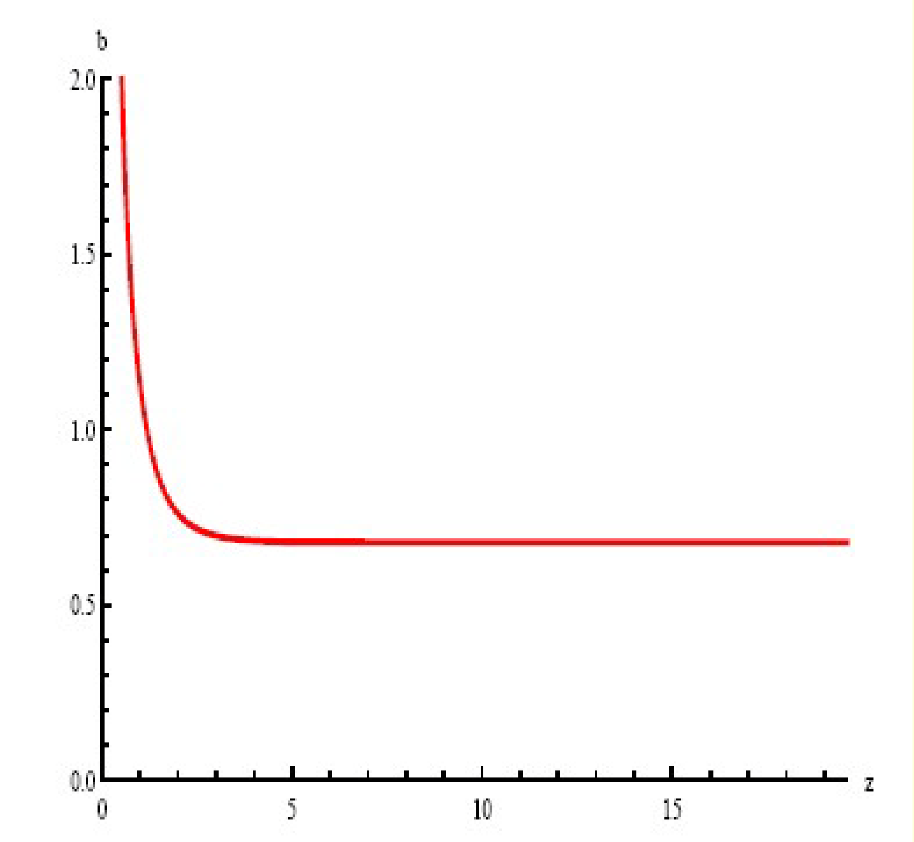
$$-A_s'' + A_s'^2 - \frac{4}{3}A_s'\phi' + \frac{2}{3}\phi'' - \frac{\lambda}{6}e^{\phi}\chi'^2 = 0$$

Mesons masses equations $-v_n'' + V_v(z)v_n = m_{v,n}^2 v_n$

Equivalent to calculate the correlation function, the eigenvalue of the function is the peak of the correlation function

The Background Solution-As

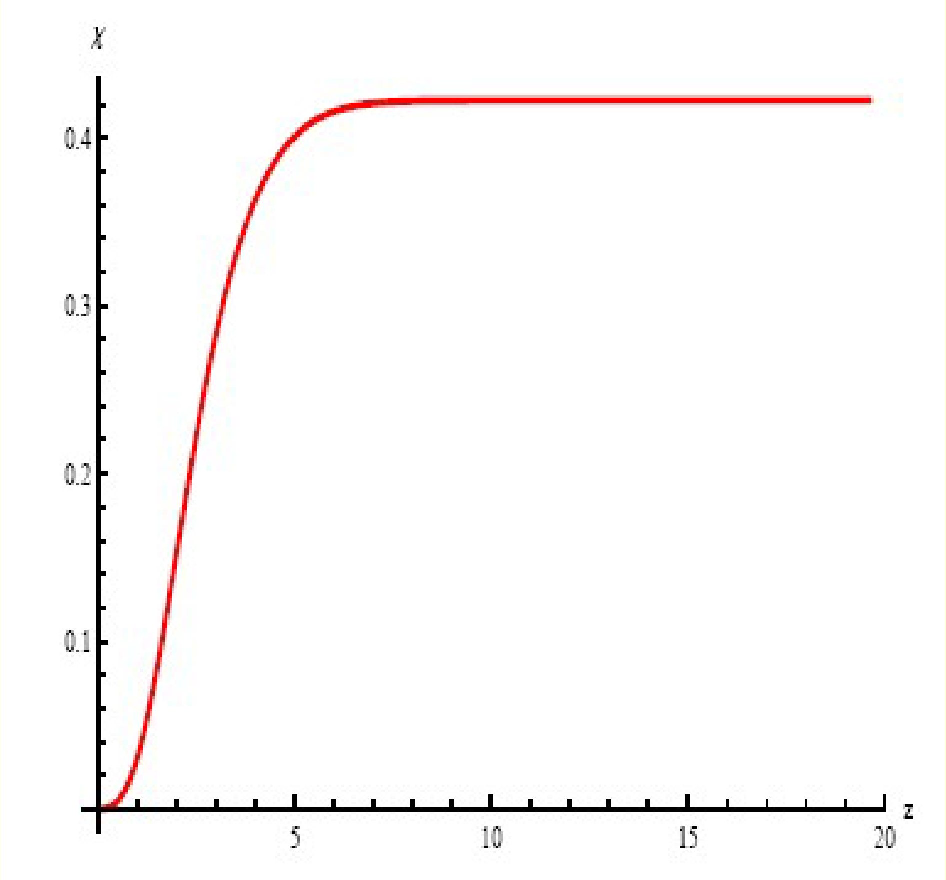
In the small z region, asymptotic AdS, in the large z region, asymptotic flat. It's possible to reproduce the linear potential. The limit value of b factor square is related to the linear slope of the potential



D.Li, M.Huang, and Q.S.Yan, arxiv:1206.2824

The Background Solution-Chi

The limit value in the IR region can help to keep the mass split of vector mesons and axial vector mesons.

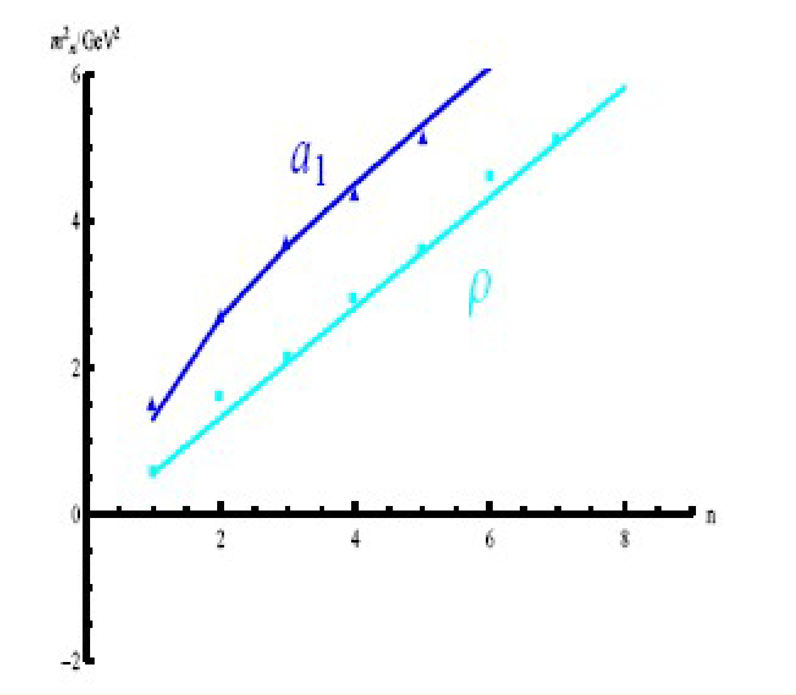


D.Li, M.Huang, and Q.S.Yan, arxiv:1206.2824

Rho-a masses

The chiral symmetry breaking is realized in lower lying states and kept in high excited states. The linear spectra are produced

The slopes of the two sectors are both $4\mu^2$



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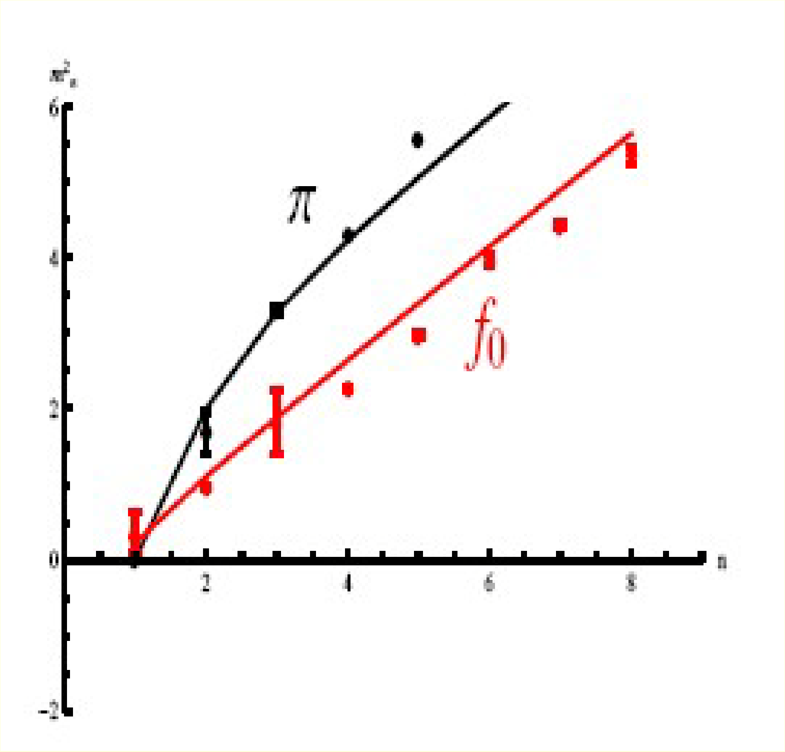
$$V_\rho = \frac{A_s'' - \phi''}{2} + \frac{(A_s' - \phi')^2}{4}$$

$$V_{a_1} = \frac{A_s'' - \phi''}{2} + \frac{(A_s' - \phi')^2}{4} + g_5^2 \chi^2 e^{2A_s}$$

pi-f0 masses

The pion mass is arout 140 MeV, and the linear spectra are produced. The chiral symmetry breaking are kept at high excited states

The slopes are also $4\mu^2$



D.Li, M.Huang, and Q.S.Yan, arxiv:1206.2824

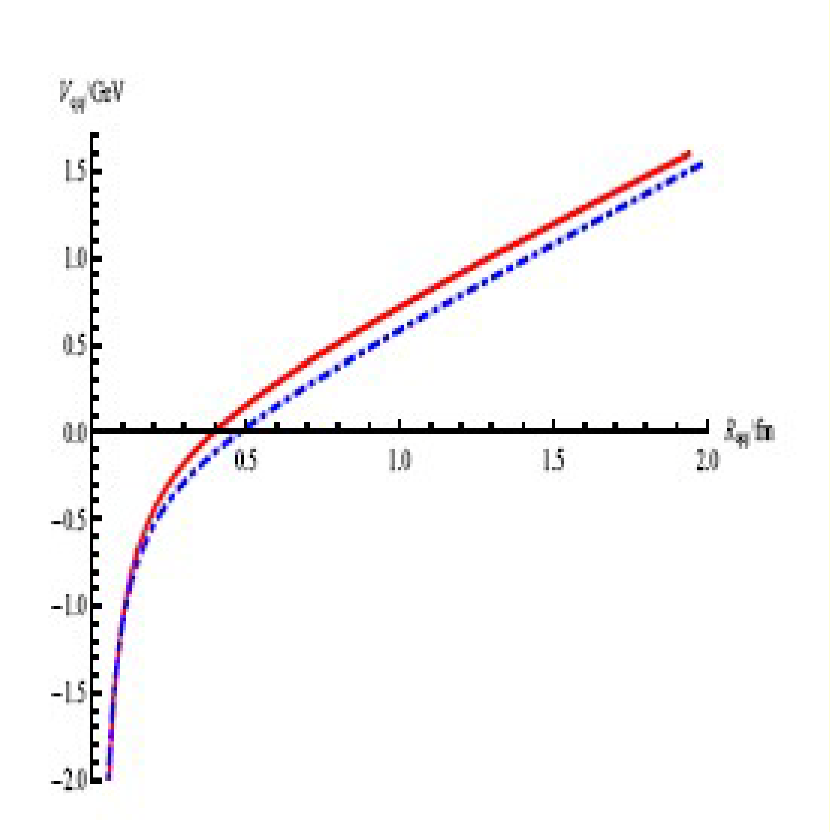
$$V_s = \frac{3A_s'' - \phi''}{2} + \frac{(3A_s' - \phi')^2}{4} + e^{2A_s}\partial_\chi^2 V(\chi);$$

$$V_s = -\frac{3A_s'' - \phi'' + 2\chi''/\chi - 2\chi'^2/\chi^2}{2} + \frac{(3A_s' - \phi' + 2\chi'/\chi)^2}{4} + g_5^2\chi^2 e^{2A_s}$$

The quark antiquark potential

The linear potential are produced. The red line are calculated from the model, the blue line is the result of the Cornell potential.

The slope of the linear part is: $\sigma_s \approx 4\mu^2$



D.Li, M.Huang, and Q.S.Yan, arxiv:1206.2824

Conclusion and Discussion

By introducing the back-reaction of the dilaton and the condensate part to the geometric, we reproduced the three aspects of QCD vacuum---the linear spectra, the linear potential and the chiral symmetry breaking simultaneously for the first time. And the background geometric was solved in a self-consistent way.

The slope of the linear potential and the linear spectra are both proportinal to $4\mu^2$, which is consistent with the consideration that the two phenomenon have the same origin. And the dilaton field may reflect the gluon dynamics that induces the confinement.

At zero temperature it works quite well, and we need to test it in finite temperature case, and study the phase transition behavior of it.

Thank you