Confinement potential from a holographic approach to strong interactions

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Based on: S.A. and T.D. Solomko, J. Phys. G 10 (2022) 105003 [2208.02604]

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The main unsolved problem in strong interactions:

CONFINEMENT

Cornell potential

The detailed lattice simulations of the form of the heavy-quark potential yields

$$V(r) = -\frac{\kappa}{r} + \sigma r + \text{const}$$

G. S. Bali, *QCD forces and heavy quark bound states*, Phys. Rept. 343 (2001), 1-136, [hep-ph/0001312]

This result imposes a serious restriction on viable phenomenological approaches modeling the dynamics of non-perturbative strong interactions: In the non-relativistic limit, they should be able to reproduce this potential

One of such promising approaches that passes the given test is the so-called **Soft-Wall (SW) holographic model**

Holographic approach to QCD
(= AdS/QCD approach)

The approach is motivated by the
<u>AdS/CFT correspondence</u>
in string theory

AdS/CFT correspondence
(= gauge/gravity duality = holographic duality)

Qualitativelly:

Strong coupling problems in non-abelian QFT ⇔ Classical Problem in a curved higher-dimensional space

g^2, N_c

$\lambda \equiv g^2 N$ T'Hooft coupling

$g_s, \alpha' = l_s^2$ String coupling and string tension

Source for major inspiration! (a great number of related models in the last 25 years)

(Maldacena, 1997 - *the most cited work in theoretical physics*!)

Although the holographic duality was not proven, it motivated construction of numerous phenomenological models for non-perturbative strong interactions which often had an unexpected predictability comparable with old traditional approaches

The essence of the holographic method

$$Z_{\rm YM}[J] \equiv e^{-W_{\rm YM}[J]} = \int \mathcal{D}\phi\, e^{-S_{\rm YM} - \int d^4x\, J\mathcal{O}}$$

source (J)

operator in QFT ($\mathcal{O}$)

$$\boxed{W_{\rm YM}[J] = S_{\rm grav}[\Phi_0]\big|_{\Phi_0 = J}}$$

$$\Phi_0 \equiv \Phi_{\partial \rm AdS}$$

The output of the holographic models: **Correlation functions**

Poles of the 2-point correlator → mass spectrum

Residues of the 2-point correlator → decay constants

Residues of the 3-point correlator → transition amplitudes

Alternative way for extracting the mass spectrum is to find normalizable modes of e.o.m.

Some applications

- ❑ Meson, baryon and glueball spectra
- ❑ Low-energy strong interactions (chiral dynamics)
- ❑ Hadronic formfactors
- ❑ Thermodynamic effects (QCD phase diagram)
- ❑ Description of quark-gluon plasma
- ❑ Condensed matter (high temperature superconductivity *etc.*)
- ❑ …

Deep relations with other approaches

- ➢ Light-front QCD
- ➢ QCD sum rules in the large-N_c limit
- ➢ Chiral perturbation theory supplemented by infinite number of vector mesons
- ➢ Renormalization group methods

Phenomenological bottom-up AdS/QCD models

Typical ansatz:

$$S = \int d^4x dz \sqrt{g}\, F(z) \mathcal{L} \qquad F(0) = 1$$

$$g = |\det g_{MN}|$$

AdS: $ds^2 = \frac{R^2}{z^2}(dx_\mu dx^\mu - dz^2), \qquad z > 0$

AdS/CFT: operators of 4D theory <-> fields in 5D theory

Vector mesons: $V_M(x,\epsilon) \leftrightarrow \bar{q}\gamma_\mu q$ or $V_M(x,\epsilon) \leftrightarrow \bar{q}\gamma_\mu \vec{\tau} q$

$A_M(x,\epsilon) \leftrightarrow \bar{q}\gamma_\mu\gamma_5 q$ or $A_M(x,\epsilon) \leftrightarrow \bar{q}\gamma_\mu\gamma_5 \vec{\tau} q$

From the AdS/CFT recipes: $m_5^2 R^2 = (\Delta - J)(\Delta + J - 4) \qquad J = 0, 1$

Masses of 5D fields are related to the canonical dimensions of 4D operators!

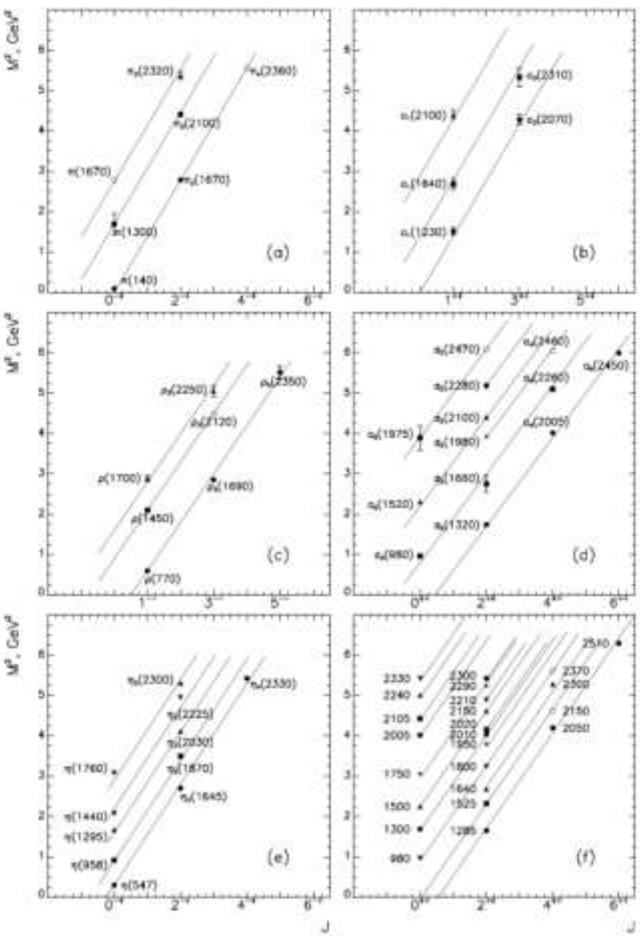
In the given cases: $\Delta = 3,\ J = 1 \Rightarrow m_5^2 = 0$ gauge 5D theory!

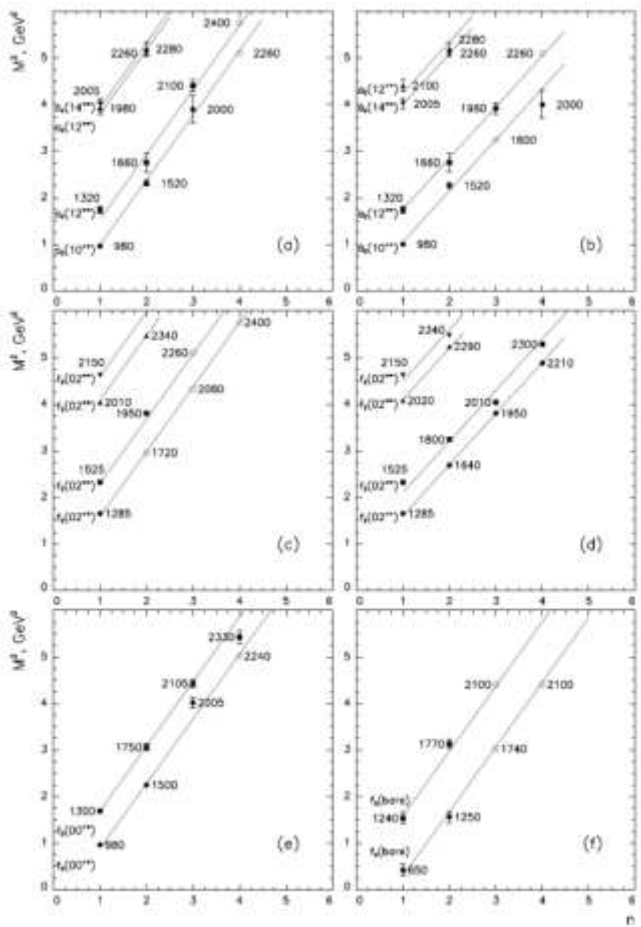
Confinement → linear Regge trajectories

$$m_n^2 \sim n$$

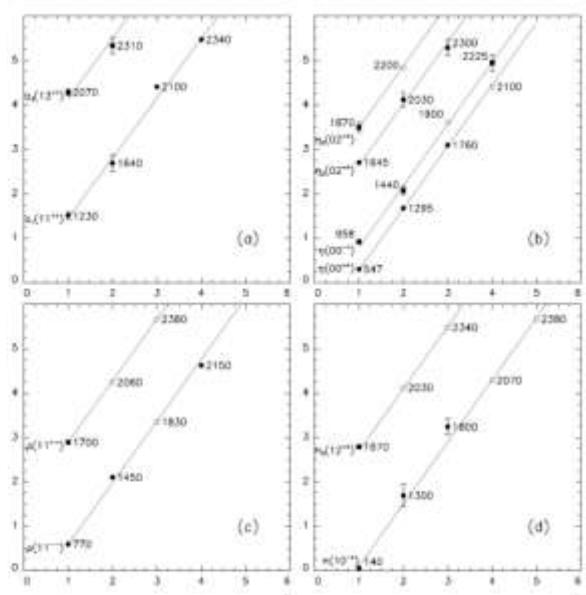
Rich source of spectral data on the light mesons – proton-antiproton annihilation

(A.V. Anisovich, V.V. Anisovich and A.V. Sarantsev, PRD (2000); D.V. Bugg, Phys. Rept. (2004))





Examples



Realization of linear Regge trajectories in the bottom-up holographic approach to QCD?

Soft-wall holographic model

A. Karch, E. Katz, D. T. Son, M. A. Stephanov, PRD 74, 015005 (2006)

$$S = \int d^4x\, dz \sqrt{g}\, \underline{e^{-cz^2}}\, \mathcal{L}$$

A mass scale (c)

"Dilaton" background (e^{-cz^2})

In a sense, the background in holographic action provides a phenomenological model for non-perturbative gluon vacuum in QCD

Alternative formulation of the SW holographic model:

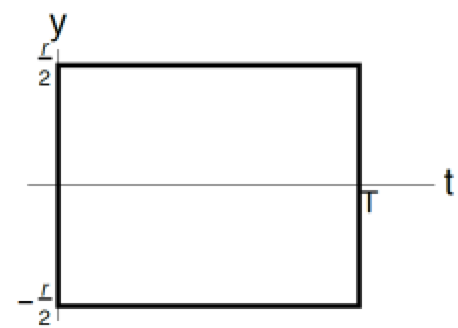
“Dilaton” background -> modified AdS metric (O. Andreev, PRD (2006))

$$g_{MN} = \text{diag}\left\{\frac{R^2}{z^2}h, \dots, \frac{R^2}{z^2}h\right\}, \qquad h = e^{-2cz^2}$$

This formulation is convenient to study the confinement properties. In particular, a Cornell like confinement potential for heavy quarks was derived (O. Andreev, V. Zakharov, PRD (2006))

But only in the case of background of the simplest vector SW model! **Generalizations?**

The main steps (J. Maldacena, PRL (1998)):
Consider the Wilson loop placed in the 4D boundary



$$T \to \infty \quad \Longrightarrow \quad \langle W(\mathcal{C})\rangle \sim e^{-TE(r)}$$

Alternatively $\langle W(\mathcal{C})\rangle \sim e^{-S}$ $\Longrightarrow$ $\boxed{E = \frac{S}{T}}$

area of a string world-sheet

The natural choice for the world-sheet area is the Nambu-Goto action

$$S = \frac{1}{2\pi\alpha'} \int d^2\xi \sqrt{\det g_{MN} \partial_\alpha X^M \partial_\beta X^N}$$

Choose $\xi_1 = t$ and $\xi_2 = y$

In the given model $$S = \frac{TR^2}{2\pi\alpha'} \int_{-r/2}^{r/2} dy \, \frac{h}{z^2} \sqrt{1 + z'^2}, \qquad z' = dz/dy$$

Omitting details, the final result is

$$r = 2\sqrt{\frac{\lambda}{c}} \int_0^1 dv \, \frac{h_0}{h} \frac{v^2}{\sqrt{1 - v^4 \frac{h_0^2}{h^2}}}$$

$$E = \frac{R^2}{\pi\alpha'} \sqrt{\frac{c}{\lambda}} \int_0^1 \frac{dv}{v^2} \frac{h}{\sqrt{1 - v^4 \frac{h_0^2}{h^2}}}$$

$$z_0 \equiv z\big|_{y=0}, \quad h_0 \equiv h\big|_{z=z_0}, \quad v \equiv \frac{z}{z_0}, \quad \lambda \equiv c z_0^2$$

Mass spectrum of vector SW model is $m_n^2 = 4|c|n, \qquad n = 1, 2, \ldots.$

Generalization to the arbitrary intercept, $m_n^2 = 4|c|(n + b)$

within this formulation, is achieved via (S.A. and T.D. Solomko, EPJC (2022))

$$h = e^{-2cz^2} \;\rightarrow\; h = e^{-2cz^2} U^4(b, 0, |cz^2|)$$

Tricomi function

The final result for this generalization is

$$r = 2\sqrt{\frac{\lambda}{c}} \int_0^1 dv \, \frac{U^4(b,0,\lambda)}{U^4(b,0,\lambda v^2)} \frac{v^2 e^{2\lambda(1-v^2)}}{\sqrt{1 - v^4 e^{4\lambda(1-v^2)} \frac{U^8(b,0,\lambda)}{U^8(b,0,\lambda v^2)}}},$$

$$E = \frac{R^2}{\pi\alpha'}\sqrt{\frac{c}{\lambda}} \left[\int_0^1 \frac{dv}{v^2} \left(\frac{e^{2\lambda v^2} U^4(b,0,\lambda v^2)}{\sqrt{1 - v^4 e^{4\lambda(1-v^2)} \frac{U^8(b,0,\lambda)}{U^8(b,0,\lambda v^2)}}} - D \right) - D \right]$$

Here $D = U^4(b, 0, 0)$

The same calculation can be made for the scalar SW model, where

$$h = e^{2cz^2/3} U^{4/3}(b, -1, cz^2)$$

$$r = 2\sqrt{\frac{\lambda}{c}} \int_0^1 dv \, \frac{U^{4/3}(b,-1,\lambda)}{U^{4/3}(b,-1,\lambda v^2)} \frac{v^2 e^{2\lambda(1-v^2)/3}}{\sqrt{1 - v^4 e^{4\lambda(1-v^2)/3} \frac{U^{8/3}(b,-1,\lambda)}{U^{8/3}(b,-1,\lambda v^2)}}},$$

$$E = \frac{R^2}{\pi\alpha'}\sqrt{\frac{c}{\lambda}} \left[\int_0^1 \frac{dv}{v^2} \left(\frac{e^{2\lambda v^2/3} U^{4/3}(b,-1,\lambda v^2)}{\sqrt{1 - v^4 e^{4\lambda(1-v^2)/3} \frac{U^{8/3}(b,-1,\lambda)}{U^{8/3}(b,-1,\lambda v^2)}}} - D \right) - D \right]$$

Here $D \equiv U^{4/3}(b, -1, 0)$

Comparison with phenomenology

$$V(r) = -\frac{\kappa}{r} + \sigma r + C$$

Typical phenomenological values of the potential parameters:

- $C \approx -0.3\,\text{GeV}$
- For charmonium: $\kappa \approx 0.25$, $\sigma \approx 0.21\,\text{GeV}^2$
- For charmonium and bottomonium (works better at small distances): $\kappa \approx 0.51$, $\sigma \approx 0.18\,\text{GeV}^2$ ← **standard value of (420 MeV)^2**

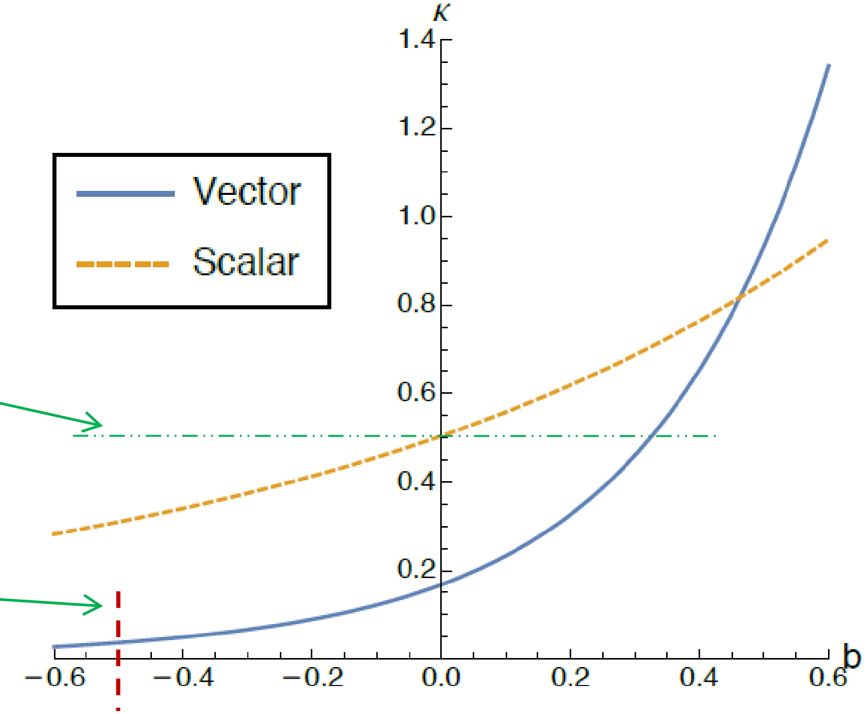
Comparison with the lattice results in SU(3) gauge theory, where $E(0.5\,\text{fm}) = 0$; quenched: $\sigma = 0.18\,\text{GeV}^2$, $\kappa = 0.295$; un-quenched: $\kappa = 0.36$.

G. S. Bali, *QCD forces and heavy quark bound states*, Phys. Rept. **343** (2001), 1-136, [hep-ph/0001312]

For fixed $\sigma_\infty = 0.18\,\mathrm{GeV}^2$

$\kappa \approx 0.51$

phenomenology



The meaning of ***b = 0*** in the scalar case?

The scalar SW spectrum: $m_n^2 = 4c(n + \Delta/2 + b), \qquad n = 0, 1, 2, \ldots$

Interpolating operator for scalar glueball: $\boxed{\beta G_{\mu\nu}^2}$ ⟹ $\boxed{\Delta = 4}$

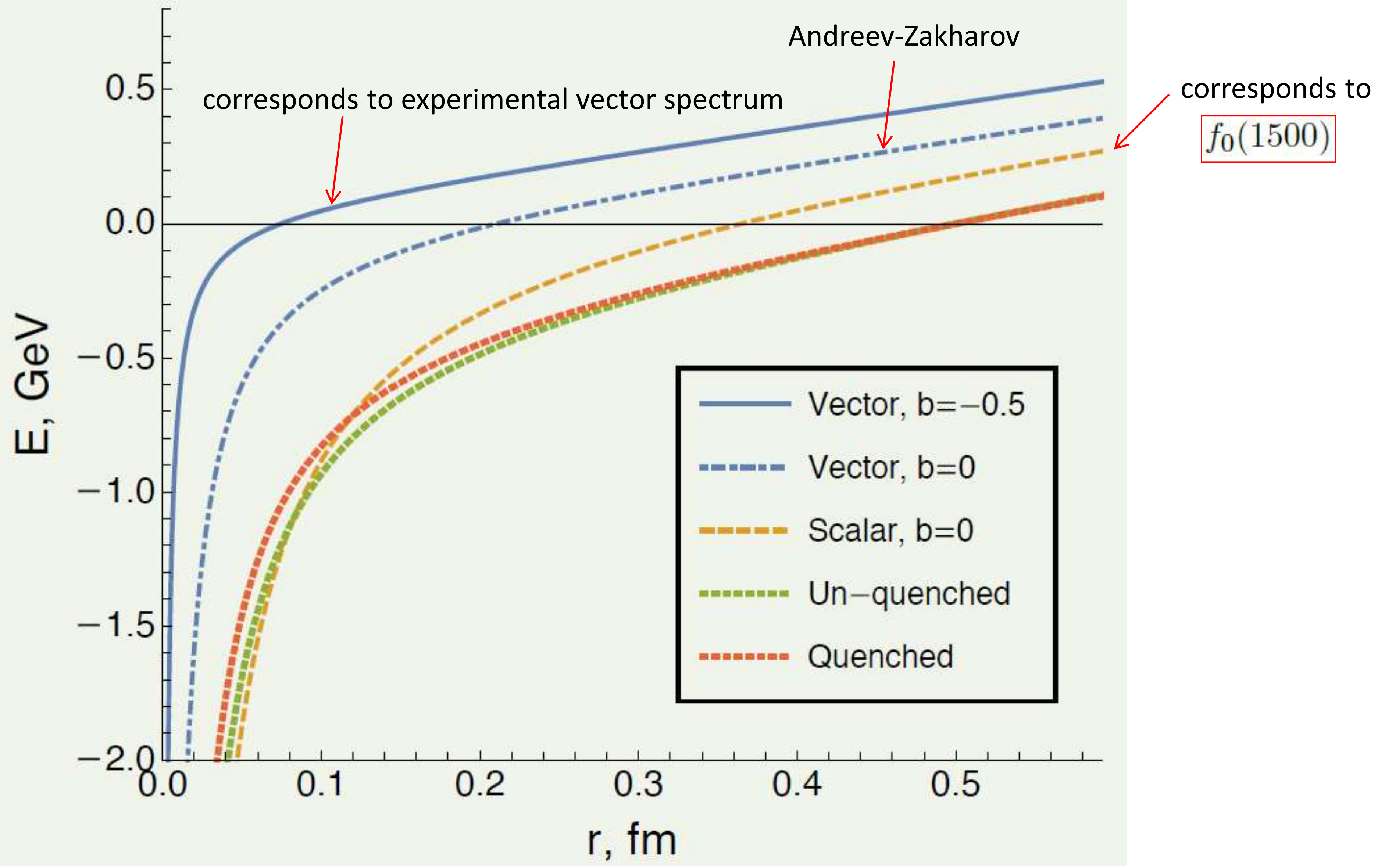
The SW spectrum for vector mesons: $m_n^2 = 4|c|(n + b), \qquad n = 1, 2, \ldots$

where the phenomenology gives $b \approx -0.5$

⟹ Prediction for the first scalar glueball: $\boxed{m_s \approx 2m_\rho}$

A natural candidate is the scalar meson $\boxed{f_0(1500)}$

The final plots



The background of scalar SW model gives a good _quantitative_ description, while the vector one reproduces only a _qualitative_ behavior!

Remark

Dynamical holography

$$S_G = \frac{1}{16\pi G_5}\int d^5x\sqrt{g_s}e^{-2\Phi}\left(R_s + 4\partial_M\Phi\partial^M\Phi - V_G^s(\Phi)\right)$$

$$\int d^4x\, e^{iqx}\langle J_\mu(x)J_\nu(0)\rangle = (q_\mu q_\nu - q^2 g_{\mu\nu})\Pi_V(Q^2)\,, \quad Q^2 = -q^2\,.$$

$$\Pi_V(Q^2) = \frac{R}{2g_5^2}\left[\sum_{n=0}^{\infty}\frac{4\Lambda^2}{Q^2 + 4\Lambda^2(n+1)} + \frac{2\Lambda^2}{Q^2}\right]$$

OPE in QCD

$$\Pi_V(Q^2)_{Q^2\to\infty} = \frac{N_c}{24\pi^2}\log\left(\frac{\mu_{\rm ren}^2}{Q^2}\right) + \frac{\alpha_s}{24\pi}\frac{\langle G^2\rangle}{Q^4} + \mathcal{O}\left(\frac{\mu_{\rm ren}^6}{Q^6}\right)$$

Conclusions

- Within the framework of Soft Wall holographic model, the Cornell potential is derived as a function of intercept of linear Regge spectrum for the vector and scalar "dilaton" backgrounds

- The scalar background leads to a *quantitative* consistency with phenomenology and lattice simulations, the agreement in the vector case is *qualitative* only

- By-product: The overall consistency of our holographic description of confinement potential seems to confirm the glueball nature of the scalar meson $f_0(1500)$

- The obtained results provide a new model demonstration of important role of scalar sector in confinement physics of strong interactions