Strongly interacting matter from holographic QCD model

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My early academic years at IOPP,CCNU

Lianshou Liu
1st generation

Pengfei Zhuang
2nd generation

Mei Huang
3rd generation

In 1994 I became one of the four graduate students at IOPP,CCNU, Prof. Lianshou Liu, the creator of IOPP, assigned Prof. Pengfei Zhuang as my supervisor, who was one of the "four young dragons" of CCNU at that time.

Content

I. Dynamical hQCD model

II. Hadron spectra

Glueball, light-flavor meson spectra

III. sQGP

Equation of state, transport properties

IV. Chiral phase transition

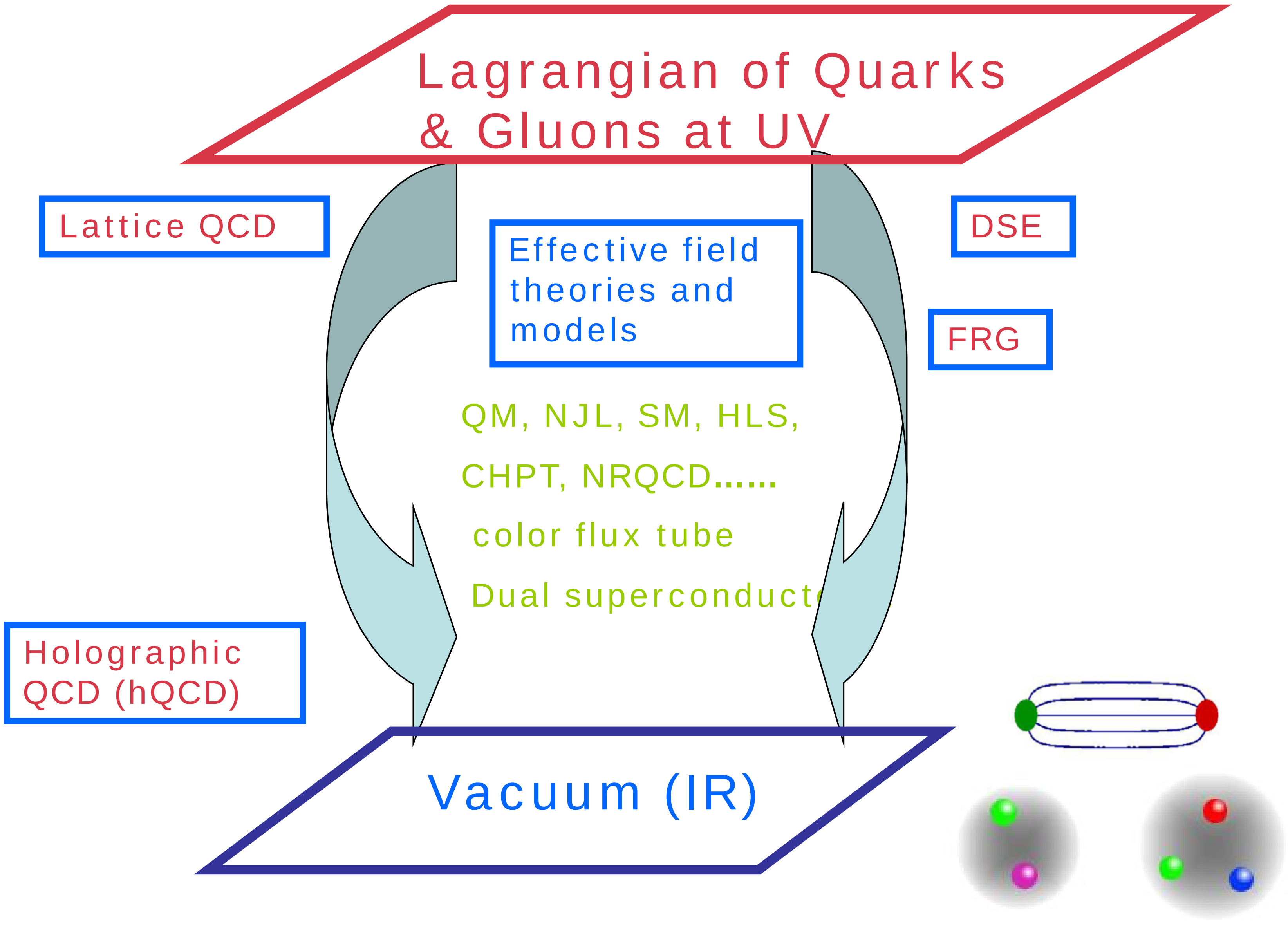
V. Conclusion and discussion

Collaborators: Danning Li, Song He, Yidian Chen
Jinfeng Liao

I. Dynamical hQCD model

----- 5D effective QCD model

Why do we need a 5D QCD model?



Holographic Duality: Gravity/QFT

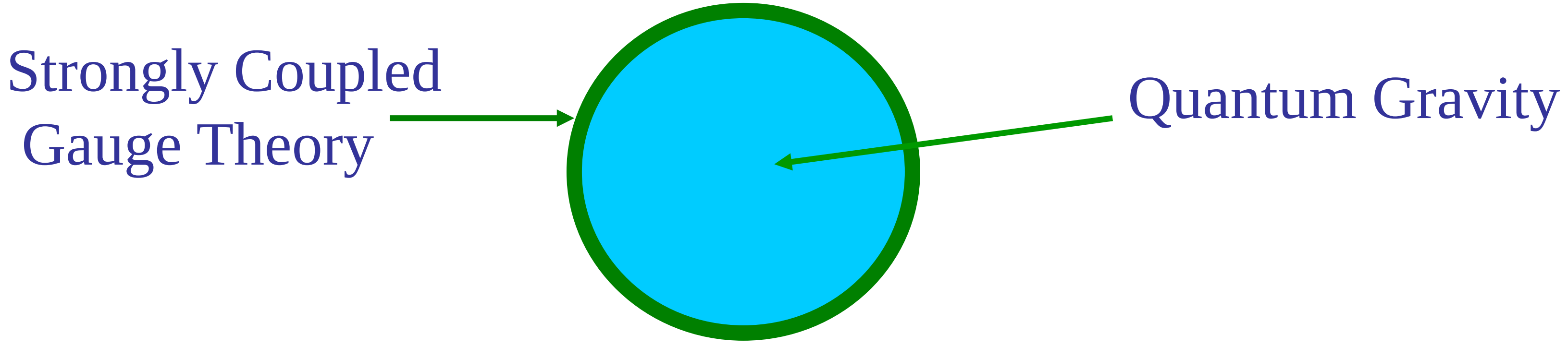
AdS/CFT : Original discovery of duality

J. M. Maldacena, Adv. Theor. Math. Phys. **2**, 231 (1998)

Supersymmetry and conformality are required for AdS/CFT.

In general, supersymmetry and conformality are not necessary

General Gravity/QFT:



Holography & Emergent critical phenomena:

When system is strongly coupled, new weakly-coupled degrees of freedom dynamically emerge.

The emergent fields live in a dynamical spacetime with an extra spatial dimension.

The extra dimension plays the role of energy scale in QFT, with motion along the extra dimension representing a change of scale, or renormalization group (RG) flow.

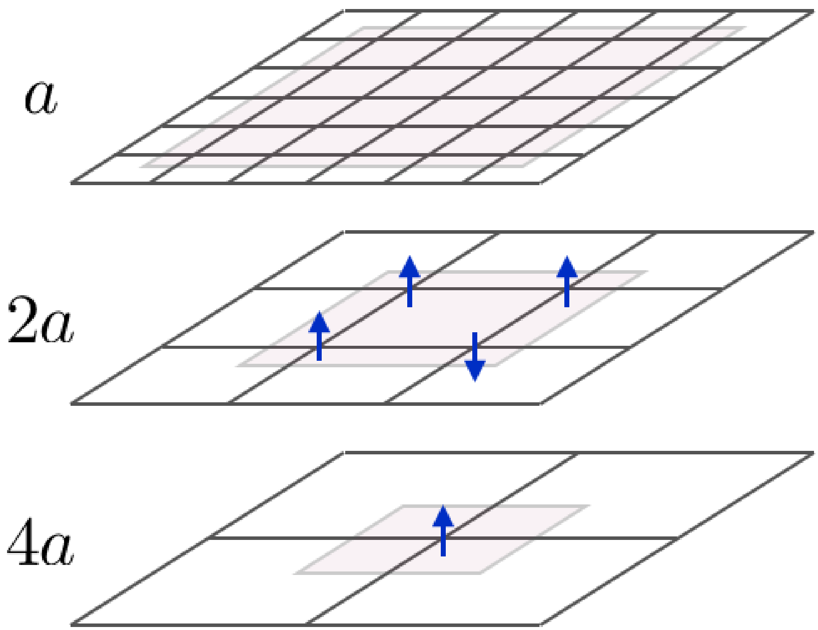
arXiv:1205.5180 Allan Adams,[1] Lincoln D. Carr,[2,3] Thomas Schäfer,[4] Peter Steinberg[5] and John E. Thomas[4]

Holographic Duality & RG flow

Coarse graining spins on a lattice: Kadanoff and Wilson

$$H = \sum_{x,i} J_i(x) \mathcal{O}^i(x)$$

J(x): coupling constant or source for the operator



$$H = \sum_{i} J_i(x, a)\, \mathcal{O}^i(x)$$

$$H = \sum_{i} J_i(x, 2a)\, \mathcal{O}^i(x)$$

$$H = \sum_{i} J_i(x, 4a)\, \mathcal{O}^i(x)$$

$$u \frac{\partial}{\partial u} J_i(x, u) = \beta_i(J_j(x, u), u)$$

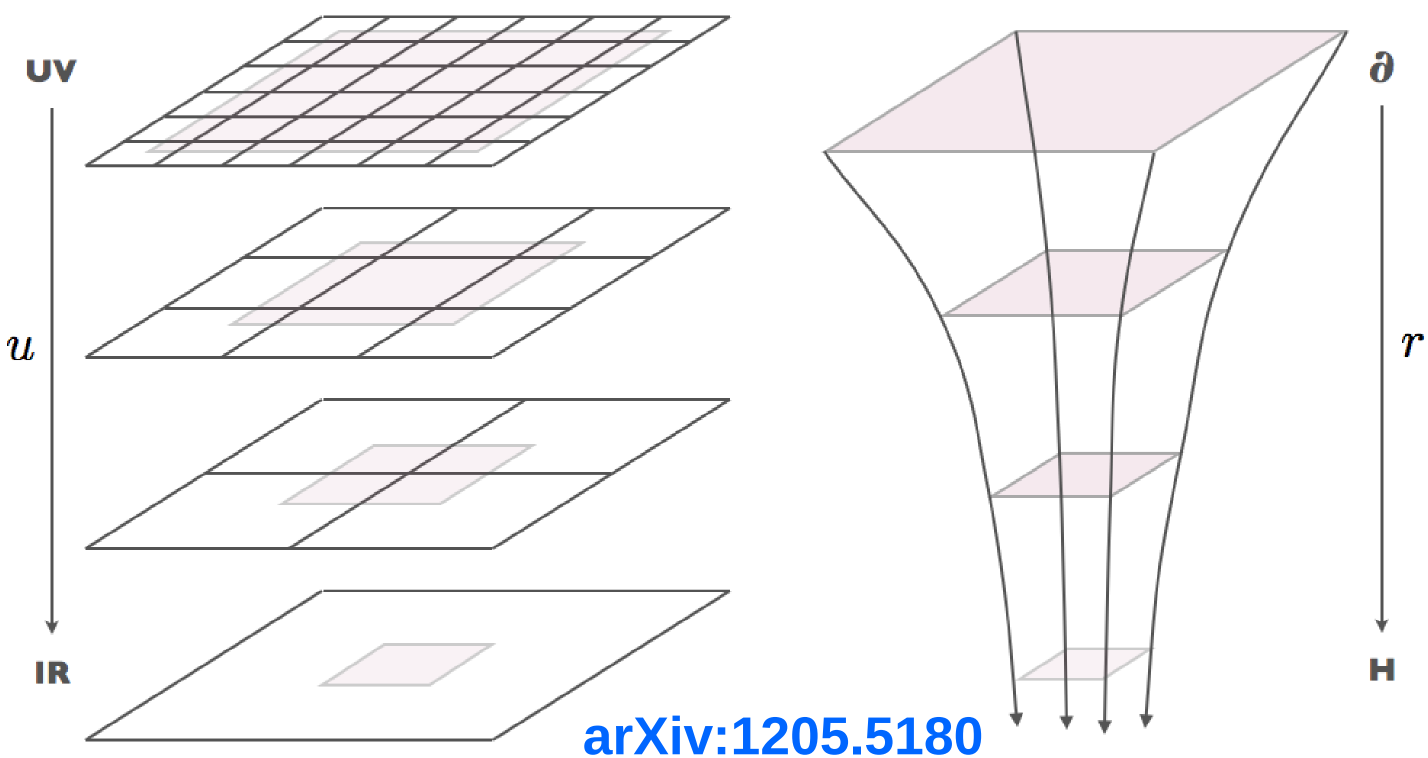
arXiv:1205.5180

Holographic Duality & RG flow

QFT on lattice equivalent to GR problem from Gravity

RG scale -> an extra spatial dimension
Coupling constant -> dynamical filed

$$J_i|_{UV} = \Phi_i|_\partial$$



arXiv:1205.5180

A systematic framework: Graviton-dilaton system

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

N=4 Super YM

conformal

AdS$_5$

$$ds^2 = \frac{L^2}{z^2} \left(dt^2 + d\vec{x}^2 + dz^2 \right)$$

$$V_E(\phi) = -\frac{12}{L^2}$$

QCD

nonconformal

deformed AdS$_5$

$$ds^2 = \frac{h(z) L^2}{z^2} \left(dt^2 + d\vec{x}^2 + dz^2 \right)$$

Dilaton field breaks conformal symmetry

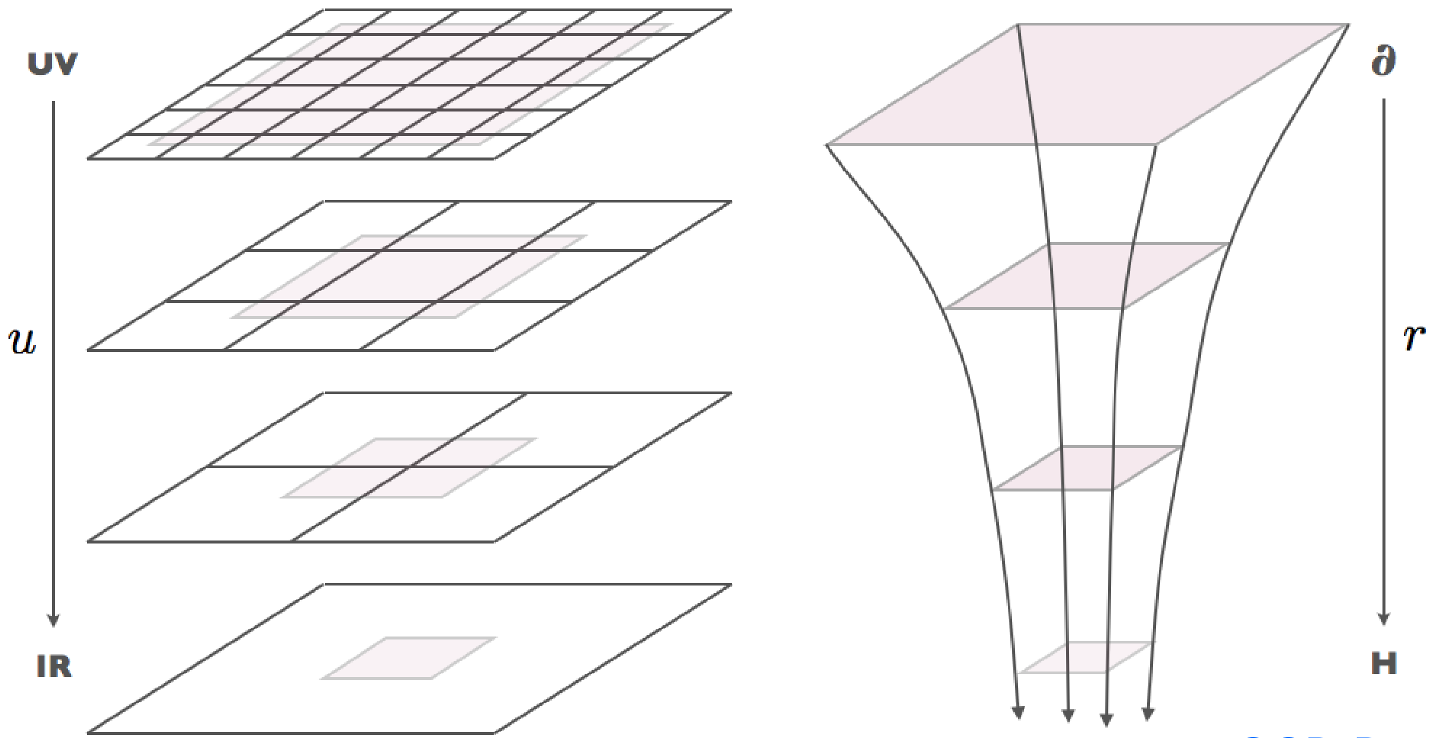
Input: QCD dynamics at IR

Solve: Metric structure, dilaton potential

Dynamical hQCD & RG

$$J_i|_{UV} = \Phi_i|_\partial$$

A AdS$_5$



From UV to IR

QCD Dynamics at IR

deformed AdS$_5$

The goal is to describe

Hadron spectra

chiral symmetry breaking

& linear confinement

Phase transitions

equation of state

Transport properties

in one systematic framework

II. Hadron spectra:

Glueball spectra
Light-flavor meson spectra

Gluonic background

Pure gluon system:

D.N. Li, M.H., JHEP2013, arXiv:1303.6929

$$\mathcal{L}_G = -\frac{1}{4} G^a_{\mu\nu}(x) G^{\mu\nu,a}(x),$$

IR: Gluon condensate $\mathrm{Tr}\langle G^2 \rangle$

Effective gluon mass $\langle g^2 A^2 \rangle$

5D action: graviton-dilaton

Gluonic background

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

$\mathrm{Tr}\langle G^2 \rangle$ $\langle g^2 A^2 \rangle$ dual to $\Phi(z)$

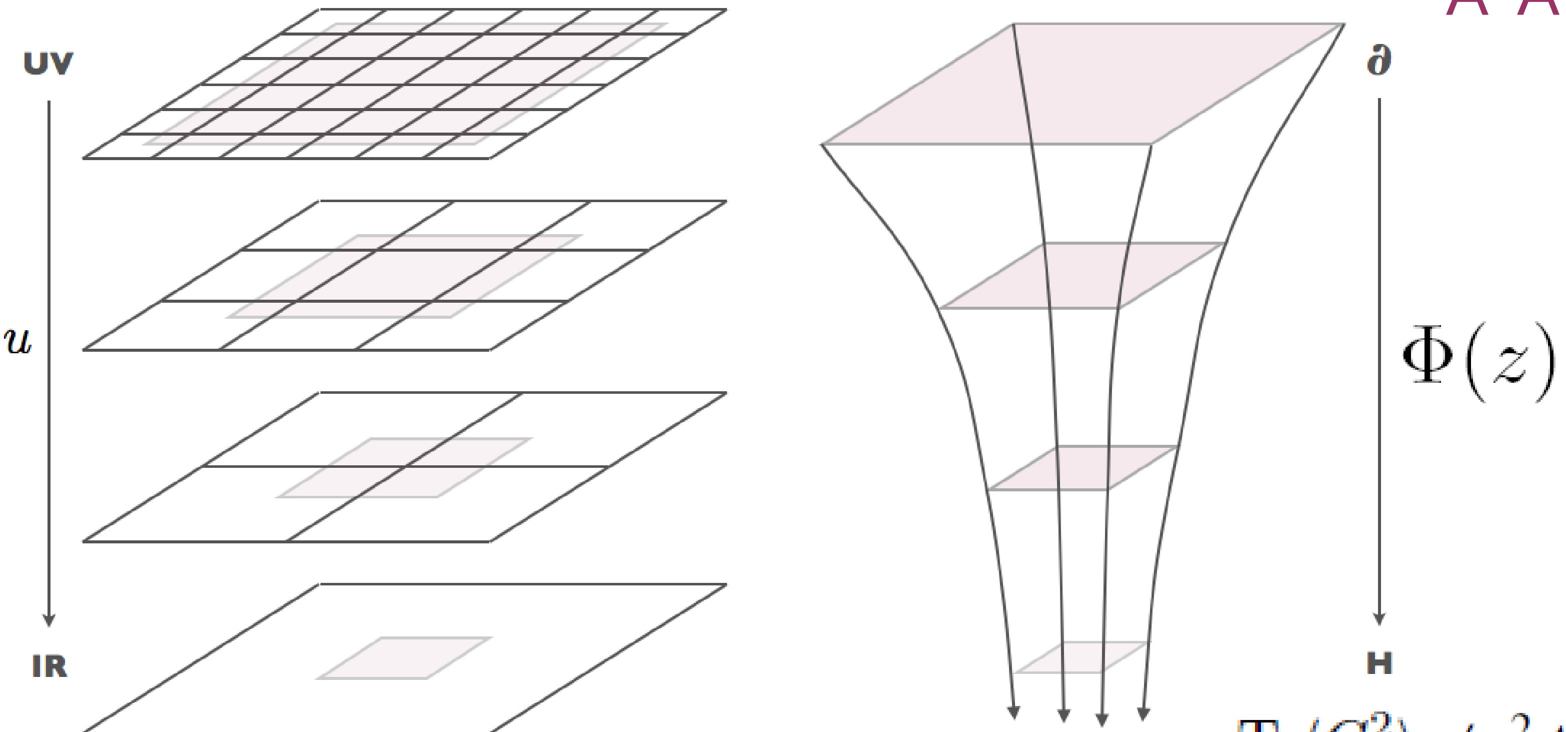
$$\Phi(z) = \mu_G^2 z^2 \tanh(\mu_{G^2}^4 z^2 / \mu_G^2)$$

$$\Phi(z) \overset{z \to 0}{\to} \mu_{G^2}^4 z^4, \qquad \Phi(z) \overset{z \to \infty}{\to} \mu_G^2 z^2.$$

Graviton-dilaton system

$$J_i|_{UV} \quad = \quad \Phi_i|_\partial$$

A AdS$_5$



From UV to IR

$\mathrm{Tr}\langle G^2\rangle \quad \langle g^2A^2\rangle$

deformed AdS$_5$

$$g^s_{MN} = b_s^2(z)(dz^2 + \eta_{\mu\nu}dx^\mu dx^\nu), \quad b_s(z) \equiv e^{A_s(z)}$$

Glueball spectra

----- Excitations from gluonic background

Holographic Duality: Dictionary

Boundary QFT

Bulk Gravity

Local operator $\mathcal{O}_i(x)$

Bulk field $\Phi_i(x,r)$

$$\Delta(d-\Delta) = m^2 L^2$$

Strongly coupled

Semi-classical

$$Z_{\rm QFT}[J_i] \; = \; Z_{\rm QG}[\Phi[J_i]]$$

$$Z_{\rm QFT}[J] \; \simeq \; e^{-I_{\rm GR}[\Phi[J]]}$$

$$\langle \mathcal{O}_1(x_1)\ldots\mathcal{O}_n(x_n)\rangle = \frac{\delta^n I_{\rm GR}[\Phi[J_i]]}{\delta J_1(x_1)\ldots\delta J_n(x_n)}\Big|_{J_i=0}$$

Scalar glueball

Excitations from the gluonic background

$$S_{\mathscr{G}} = \int d^5x \sqrt{g_s} \frac{1}{2} e^{-\Phi} \left[\partial_M \mathscr{G} \partial^M \mathscr{G} + M^2_{\mathscr{G},5} \mathscr{G}^2 \right]$$

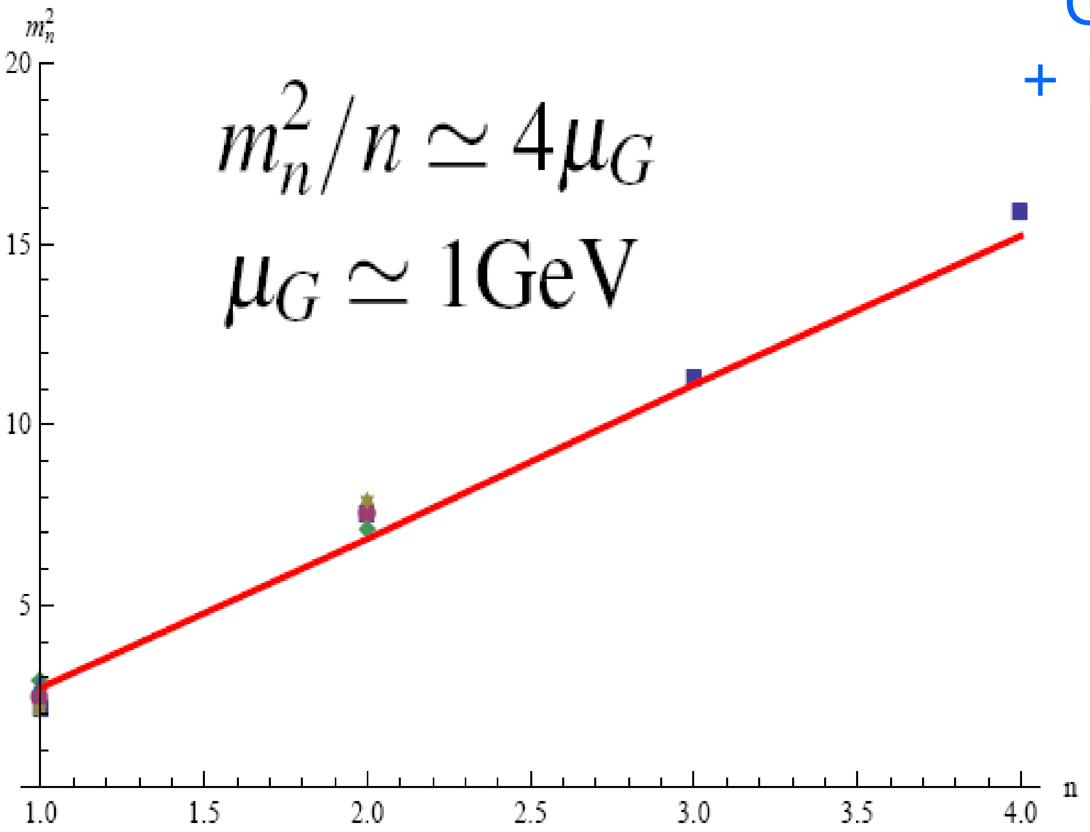
scalar glueball: $\mathscr{G}$ dual to $tr(G_{\mu\nu} G^{\mu\nu})$ $M^2_{\mathscr{G},5} = 0$

$$-\mathscr{G}_n'' + V_{\mathscr{G}} \mathscr{G}_n = m^2_{\mathscr{G},n} \mathscr{G}_n,$$

$$V_{\mathscr{G}} = \frac{3A_s'' - \Phi''}{2} + \frac{(3A_s' - \Phi')^2}{4}$$

Scalar glueball   D.N. Li, M.H., JHEP2013, arXiv:1303.6929

Ground state
+ Regge slope !



hep-lat/0508002.

[hep-lat/0510074].

[hep-lat/0103027].

[hep-lat/9901004]

Two-gluon and tri-gluon Glueball spectra:

Yidian Chen, M.H., arXiv: 1511.07018

$$M_5^2 = (\Delta - f)(\Delta + f - 4)$$

J^{PC}	$4D : \mathcal{O}(x)$	Δ	f	M_5^2	
0^{++}	$Tr(G^2)$	4	0	0	
0^{--}	$Tr(\tilde{G}\{D_{\mu_1}D_{\mu_2}G, G\})$	8	0	32	**tri-gluon**
0^{-+}	$Tr(G\tilde{G})$	4	0	0	
$1^{\pm-}$	$Tr(G\{G, G\})$	6	1	15	**tri-gluon**
2^{++}	$Tr(G_{\mu\alpha}G_{\alpha\nu} - \frac{1}{4}\delta_{\mu\nu}G^2)$	4	2	4	
2^{++}	$E_i^a E_j^a - B_i^a B_j^a - trace$	4	2	4	
2^{-+}	$E_i^a B_j^a + B_i^a E_j^a - trace$	4	2	4	
$2^{\pm-}$	$Tr(G\{G, G\})$	6	2	16	**tri-gluon**

Two-gluon and tri-gluon Glueball spectra:

C. -F. Qiao and L. Tang, "Finding the 0^{--} Glueball," Phys. Rev. Lett. **113**, 221601 (2014).

C. F. Qiao and L. Tang, arXiv:1509.00305 [hep-ph].

Tri-gluon glueball

$$j^A_{0^{--}} \sim d^{abc}[g^t_{\alpha\beta}\tilde{G}^a_{\mu\nu}][\partial_\alpha\partial_\beta G^b_{\nu\rho}][G^c_{\rho\mu}],$$
$$j^B_{0^{--}} \sim d^{abc}[g^t_{\alpha\beta}G^a_{\mu\nu}][\partial_\alpha\partial_\beta \tilde{G}^b_{\nu\rho}][G^c_{\rho\mu}],$$
$$j^C_{0^{--}} \sim d^{abc}[g^t_{\alpha\beta}G^a_{\mu\nu}][\partial_\alpha\partial_\beta G^b_{\nu\rho}][\tilde{G}^c_{\rho\mu}],$$
$$j^D_{0^{--}} \sim d^{abc}[g^t_{\alpha\beta}\tilde{G}^a_{\mu\nu}][\partial_\alpha\partial_\beta \tilde{G}^b_{\nu\rho}][\tilde{G}^c_{\rho\mu}],$$

$$j^{2^{+-},\,A}_{\mu\alpha}(x) = g_s^3 d^{abc}[G^a_{\mu\nu}(x)][G^b_{\nu\rho}(x)][G^c_{\rho\alpha}(x)]\,,$$
$$j^{2^{+-},\,B}_{\mu\alpha}(x) = g_s^3 d^{abc}[G^a_{\mu\nu}(x)][\tilde{G}^b_{\nu\rho}(x)][\tilde{G}^c_{\rho\alpha}(x)]\,,$$
$$j^{2^{+-},\,C}_{\mu\alpha}(x) = g_s^3 d^{abc}[\tilde{G}^a_{\mu\nu}(x)][G^b_{\nu\rho}(x)][\tilde{G}^c_{\rho\alpha}(x)]\,,$$
$$j^{2^{+-},\,D}_{\mu\alpha}(x) = g_s^3 d^{abc}[\tilde{G}^a_{\mu\nu}(x)][\tilde{G}^b_{\nu\rho}(x)][G^c_{\rho\alpha}(x)]\,.$$

Glueball

Yidian Chen, M.H., arXiv: 1511.07018

$$S_{\mathscr{G}} = -\frac{1}{2}\int d^5x\sqrt{g_s}e^{-p\Phi}\left(\partial_M \mathscr{G} \partial^M \mathscr{G} + M^2_{\mathscr{G},5}(z)\mathscr{G}^2\right),$$

$$S_V = -\frac{1}{2}\int d^5x\sqrt{g_s}e^{-p\Phi}\left(\frac{1}{2}F^{MN}F_{MN} + M^2_{\mathscr{V},5}(z)\mathscr{V}^2\right),$$

$$S_T = -\frac{1}{2}\int d^5x\sqrt{g_s}e^{-p\Phi}\big(\nabla_L h_{MN}\nabla^L h^{MN} - 2\nabla_L h^{LM}\nabla^N h_{NM} + 2\nabla_M h^{MN}\nabla_N h$$

$$-\nabla_M h \nabla^M h + M^2_{h,5}(z)(h^{MN}h_{MN} - h^2)\big)$$

$M_5^2(z) = M_5^2 e^{-2\Phi/3}$, $p = 1$ for even parity and $p = -1$ for odd parity.

Glueball

Yidian Chen, M.H., arXiv: 1511.07018

EOM:

$$-\mathscr{A}_n'' + V_{\mathscr{A}}\mathscr{A}_n = m^2_{\mathscr{A},n}\mathscr{A}_n,$$

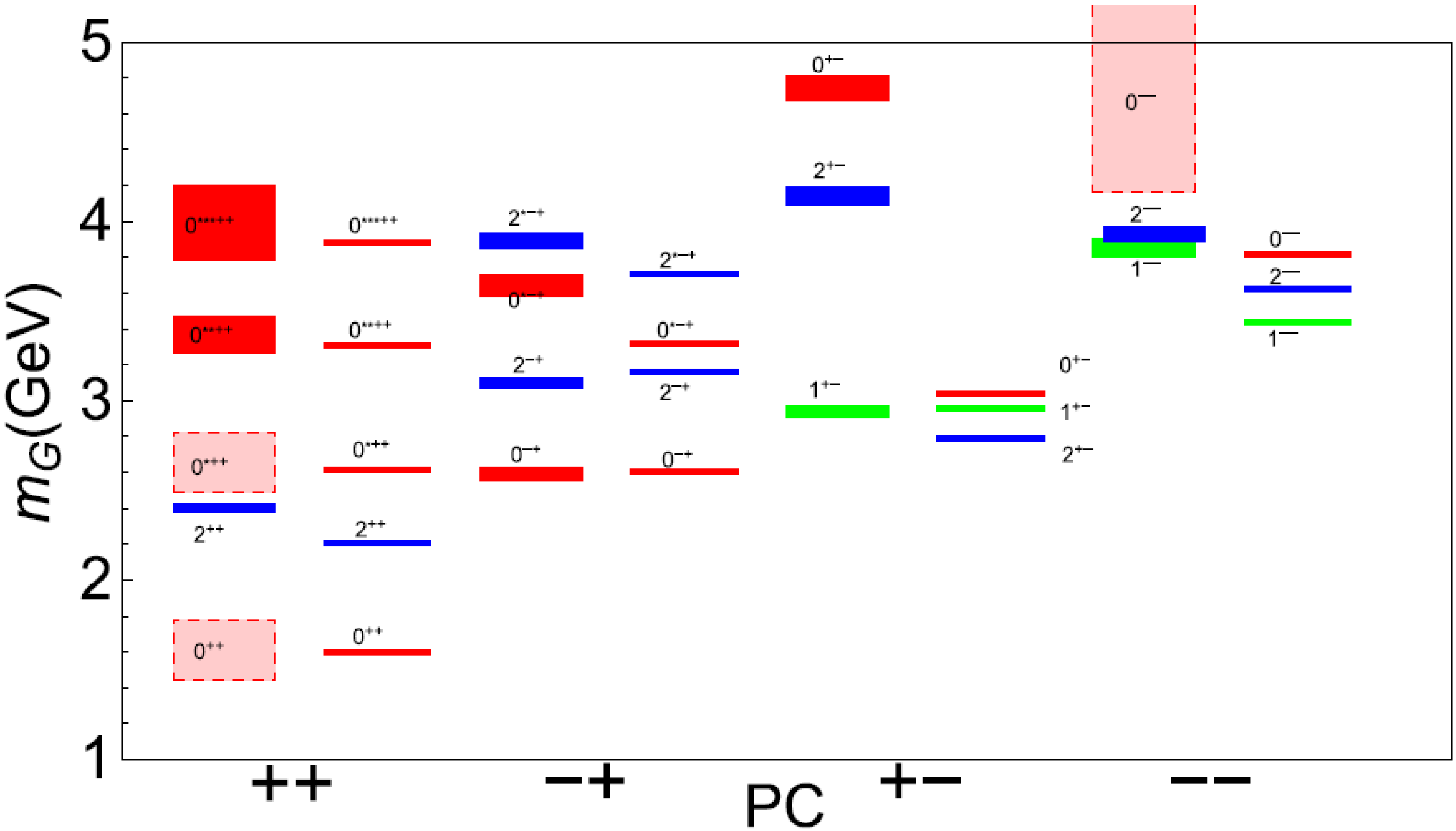
$$V_{\mathscr{A}} = \frac{cA_s'' - p\Phi''}{2} + \frac{(cA_s' - p\Phi')^2}{4} + e^{2A_s - \frac{2}{3}\Phi}M^2_{\mathscr{A},5},$$

Only one parameter determined from the Regge slope of the scalar glueball spectra:

$$\mu_G = 1\mathrm{GeV}$$

Glueball spectra:

Yidian Chen, M.H., arXiv: 1511.07018



Agree well with lattice result except three trigluon glueball 0^{--} , 0^{+-} and 2^{+-}

Glueball spectra:

Yidian Chen, M.H., to appear

J^{PC}	LQCD	Flux tube model	QCDSR	MDSM
0^{++}	1.475-1.73	1.52	1.5	1.593
0^{*++}	2.67-2.83	2.75	–	2.618
0^{**++}	3.37	–	–	3.311
0^{***++}	3.99	–	–	3.877
0^{-+}	2.59	2.79	2.05	2.606
0^{*-+}	3.64	–	–	3.317
0^{--}	5.166	2.79	3.81	3.817
0^{+-}	4.74	2.79	4.57	3.04
$0^{++\S}$	–	–	3.1	2.667
1^{+-}	2.94	2.25	–	2.954
1^{--}	3.85	–	–	3.44
2^{++}	2.4	2.84	2	2.203
2^{-+}	3.1	2.84	–	3.161
2^{*-+}	3.89	–	–	3.703
2^{+-}	4.14	2.84	6.06	2.786
2^{--}	3.93	2.84	–	3.619

All two-gluon and tri-gluon glueball spectra agree well with lattice result except three trigluon glueballs

0^{--} , 0^{+-} and 2^{+-}

These three trigluon glueballs

0^{--} , 0^{+-} and 2^{+-}

are dominated by three-gluon condensate.

Our model only considered two-gluon condensate.

Light flavor hadron spectra

Add flavor dynamics

D.N. Li, M.H., JHEP2013, arXiv:1303.6929

Action for pure gluon system: Graviton-dilaton coupling

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

Gluonic background

Action for light hadrons: KKSS model

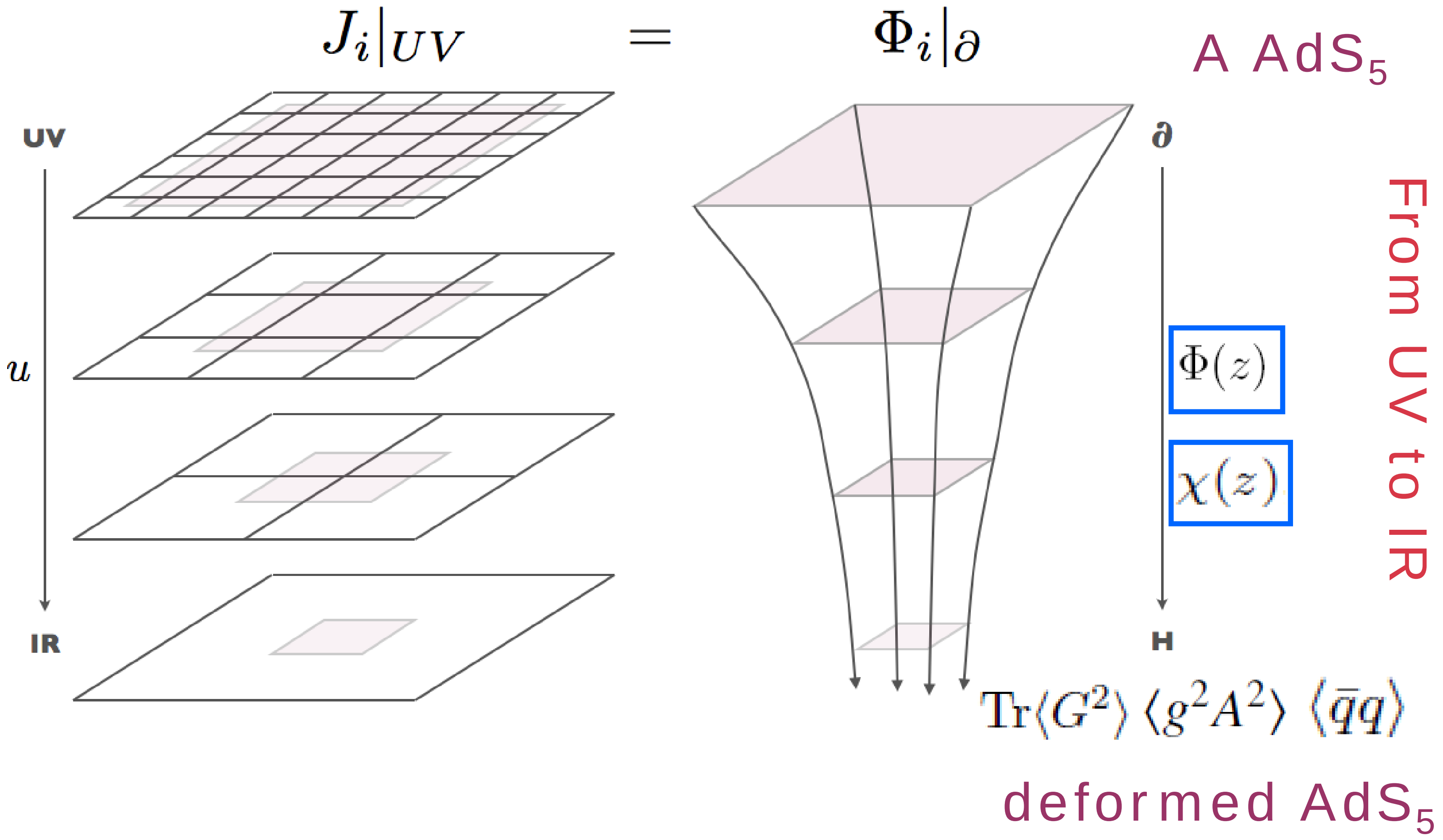
$$S_{KKSS} = -\int d^5x\sqrt{g_s}e^{-\Phi}Tr(|DX|^2 + V_X(X^+X,\Phi) + \frac{1}{4g_5^2}(F_L^2 + F_R^2))$$

5D linear sigma model

Total action:

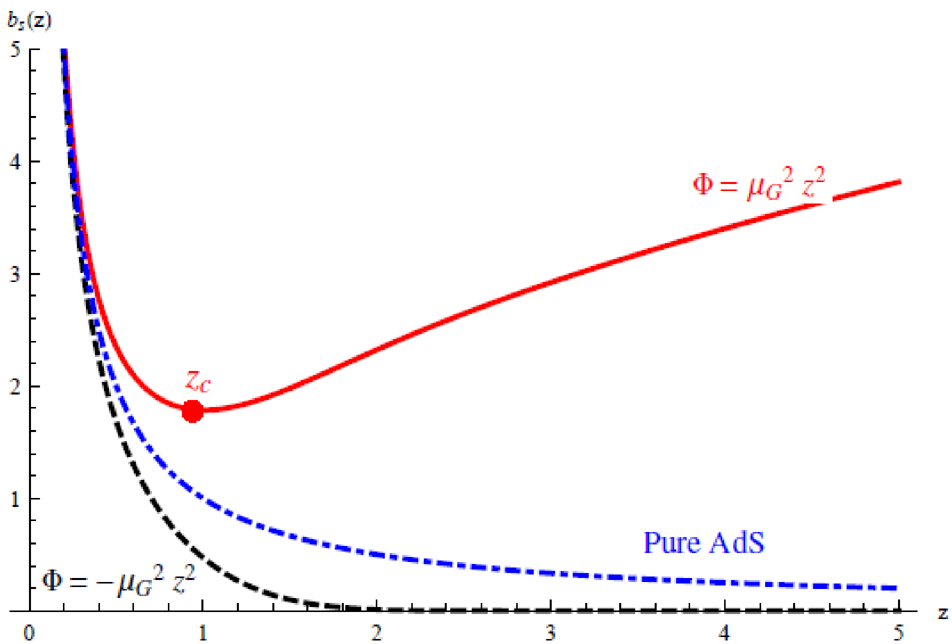
$$S = S_G + \frac{N_f}{N_c}S_{KKSS}$$

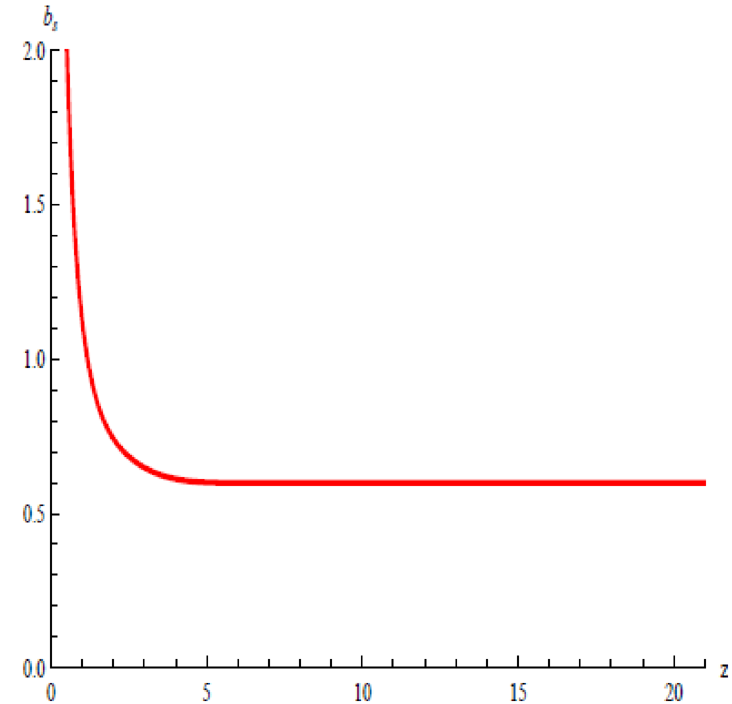
Graviton-dilaton-scalar system



Quenched background

Unquenched background





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

$$\Phi'' + (3A_s' - 2\Phi')\Phi' - \frac{3\lambda}{16}e^{\Phi}\chi'^2 - \frac{3}{8}e^{2A_s - \frac{4}{3}\Phi}\partial_\Phi\left(V_G(\Phi) + \lambda e^{\frac{7}{3}\Phi}V_C(\chi,\Phi)\right) = 0,$$

$$\chi'' + (3A_s' - \Phi')\chi' - e^{2A_s}V_{C,\chi}(\chi,\Phi) = 0.$$

$$\textit{Dilaton in Mod I}: \quad \Phi(z) = \mu_G^2 z^2$$

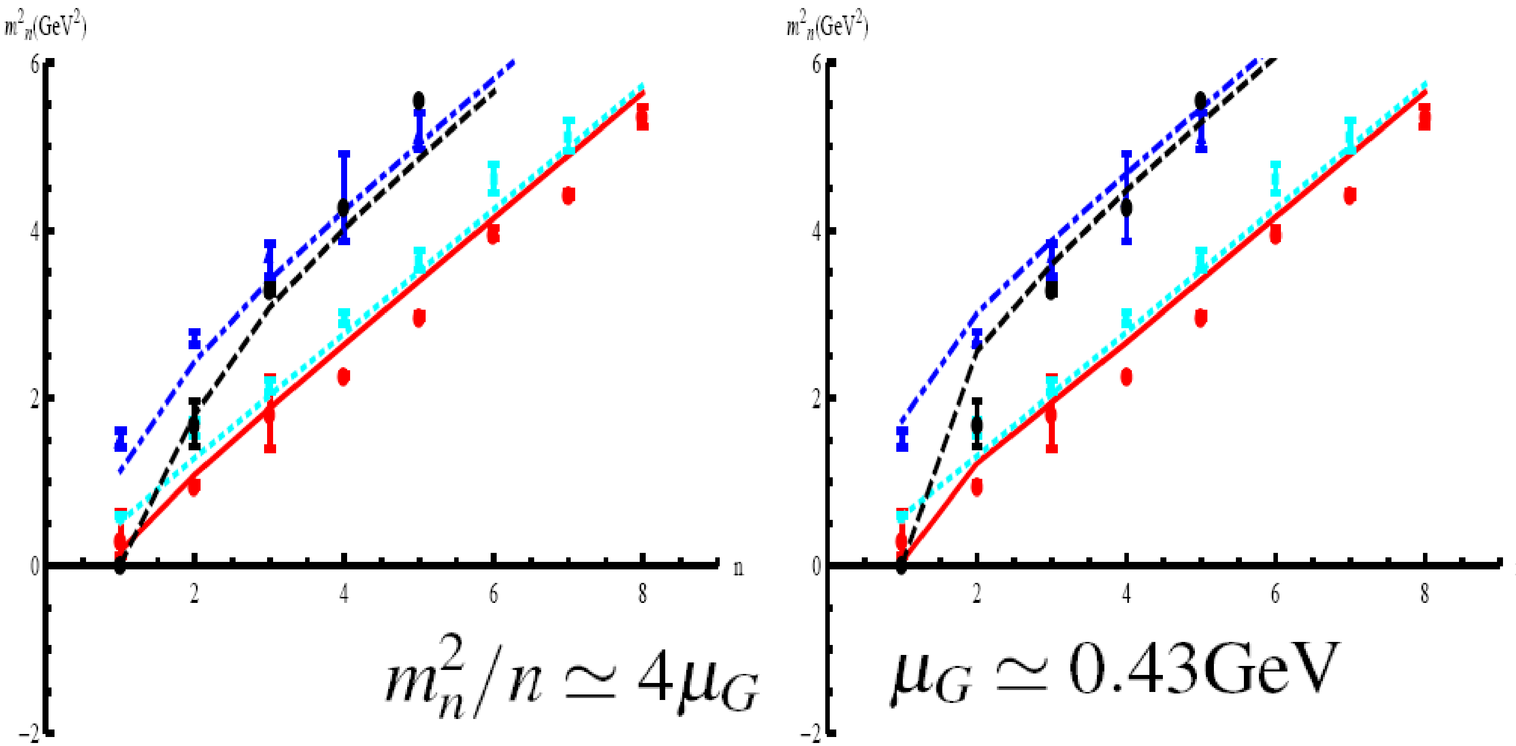
$$\textit{Dilaton in Mod II}: \quad \Phi(z) = \mu_G^2 z^2 \tanh(\mu_{G^2}^4 z^2/\mu_G^2)$$

	Mod IA	Mod IB	Mod IIA	Mod IIB
G_5/L^3	0.75	0.75	0.75	0.75
m_q (MeV)	5.8	5.0	8.4	6.2
$\sigma^{1/3}$ (MeV)	180	240	165	226
μ_G	0.43	0.43	0.43	0.43
μ_{G^2}	-	-	0.43	0.43

Table 7. Two sets of parameters.

Produced hadron spectra compared with data

D.N. Li, M.H., JHEP2013, arXiv:1303.6929



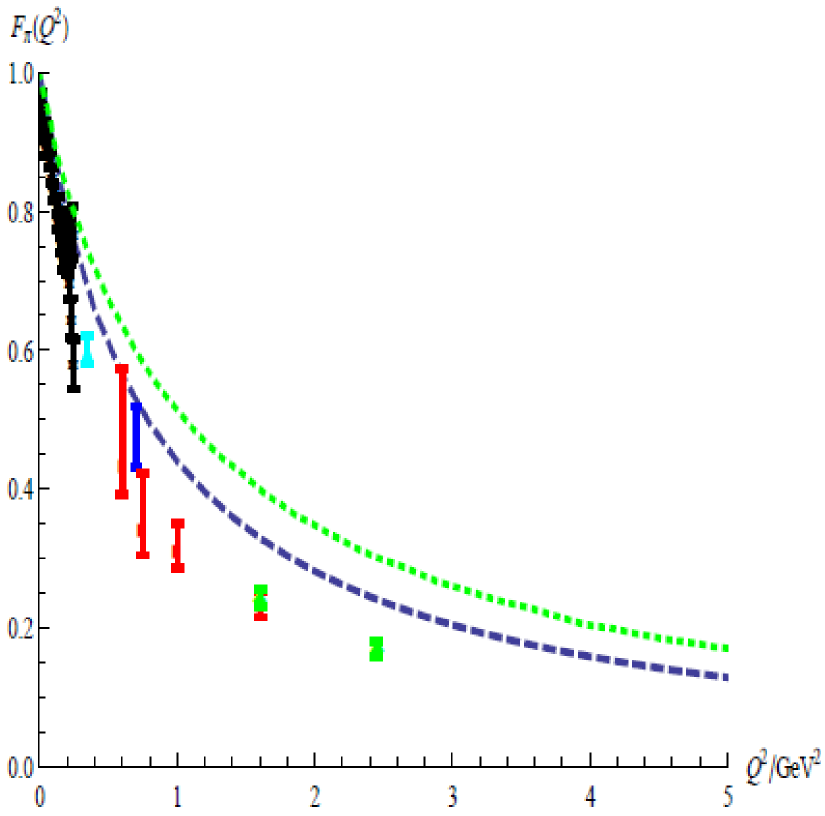
(**Mod IA**) (**Mod IB**)

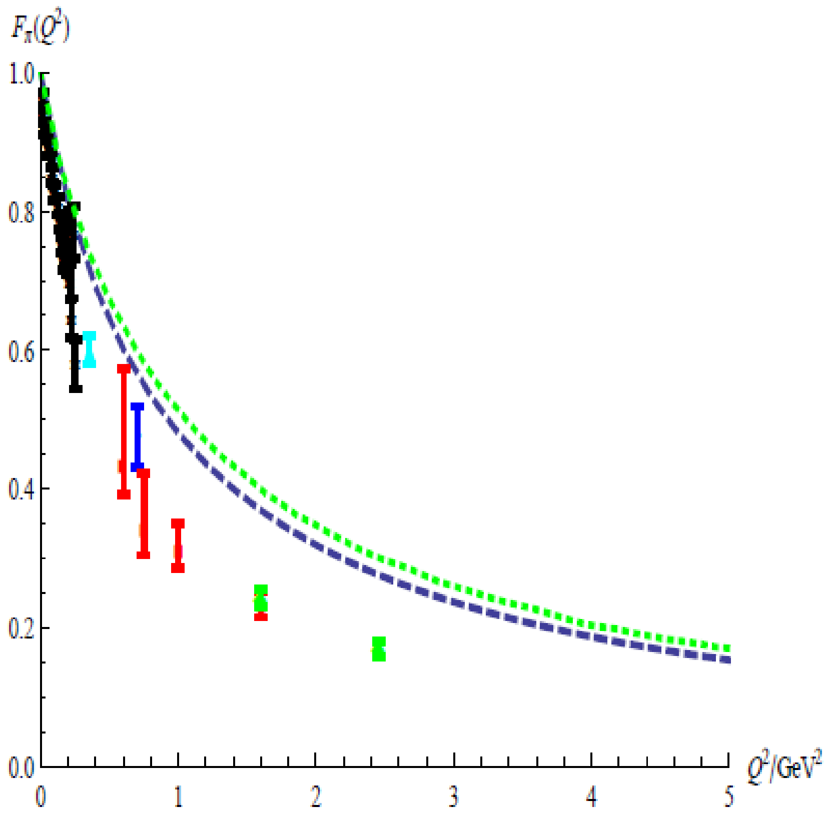
Ground states: chiral symmetry breaking

Excitation states: linear confinemnt

Produced pion form factor compared with data

D.N. Li, M.H., JHEP2013, arXiv:1303.6929





III. sQGP

Equation of state

Phase transition and EOS

5D graviton action:

$$S_{5D} = \frac{1}{16\pi G_5}\int d^5x\sqrt{-g^E}\left(R - \frac{4}{3}\partial_\mu\phi\partial^\mu\phi - V_E(\phi)\right)$$

$$ds_S^2 = \frac{L^2 e^{2A_s}}{z^2}\left(-f(z)dt^2 + \frac{dz^2}{f(z)} + dx^i dx^i\right),$$

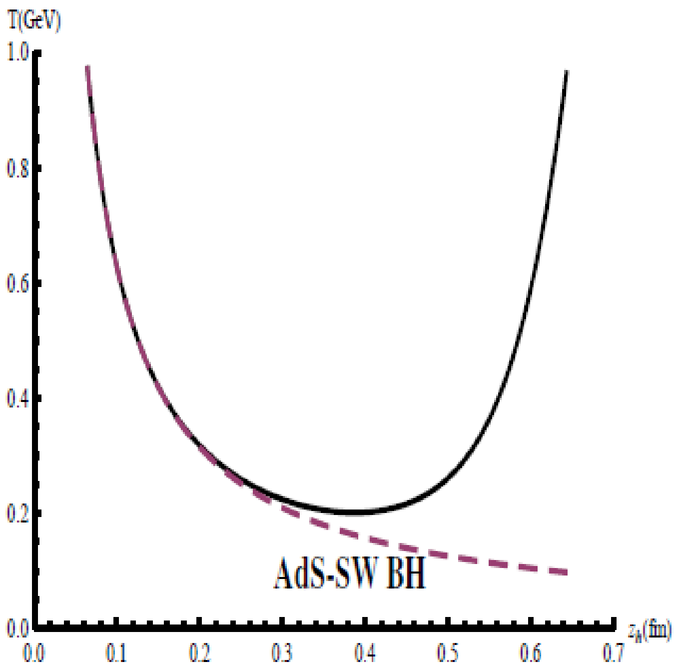
Metric structure, blackhole, Dilaton field and Dilaton potential should be solved self-consistently from the Einstein equations.

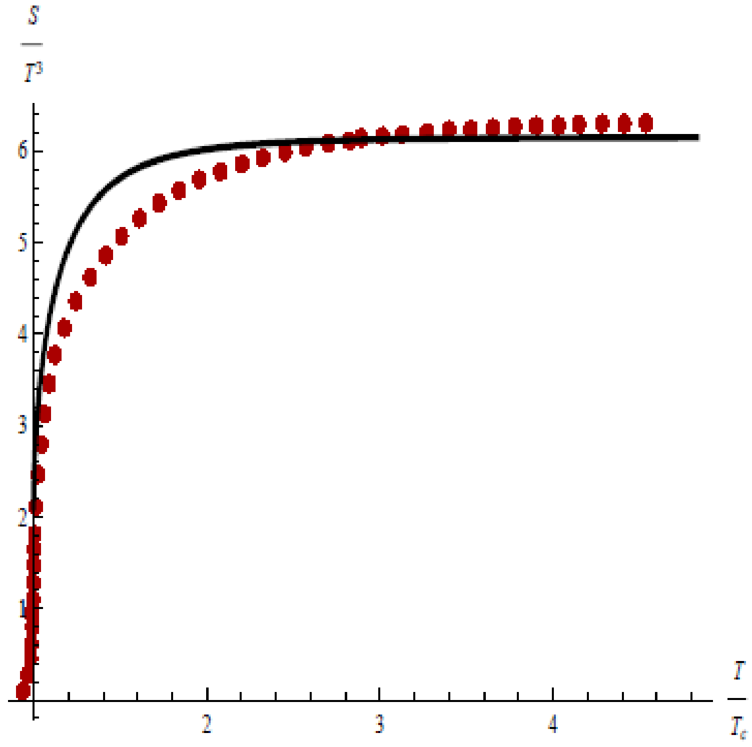
$$\phi(z) = \phi_0 + \phi_1 \int_0^z \frac{e^{2A_s(x)}}{x^2}\,dx + \frac{3A_s(z)}{2}$$
$$+ \frac{3}{2}\int_0^z \frac{e^{2A_s(x)} \int_0^x y^2 e^{-2A_s(y)} A_s'(y)^2 dy}{x^2}\,dx,$$
$$f(z) = f_0 + f_1 \left(\int_0^z x^3 e^{2\phi(x)-3A_s(x)}\,dx\right),$$
$$V_E(\phi) = \frac{e^{\frac{4\phi(z)}{3}-2A_s(z)}}{L^2}$$
$$\left(z^2 f''(z) - 4f(z)\left(3z^2 A_s''(z) - 2z^2\phi''(z) + z^2\phi'(z)^2 + 3\right)\right).$$

D.N, Li, S. He, M. Huang, Q. S. Yan, arXiv:1103.5389

$$T = \frac{|f'(z_h)|}{4\pi}.$$

$$s = \frac{A_{area}}{4G_5 V_3} = \frac{L^3}{4G_5}\left(\frac{e^{A_s - \frac{2}{3}\phi}}{z}\right)^3.$$



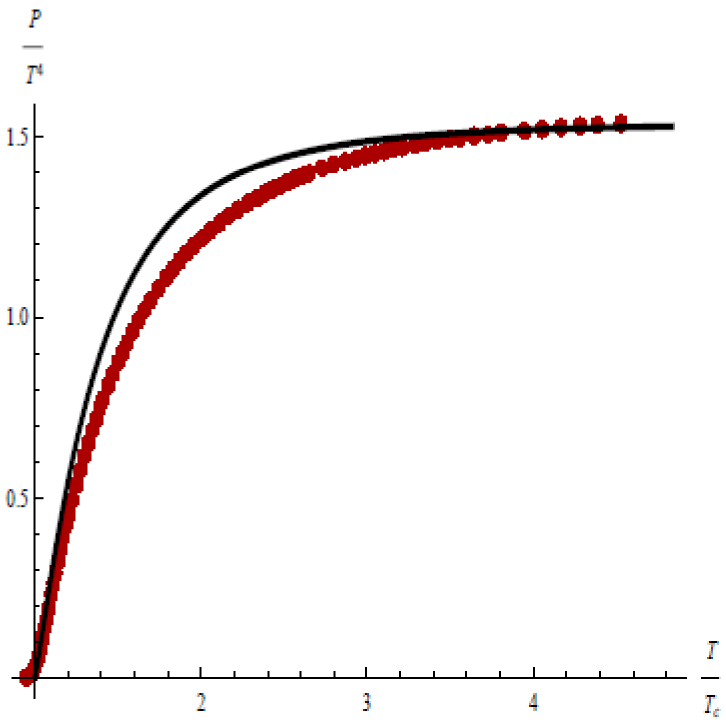


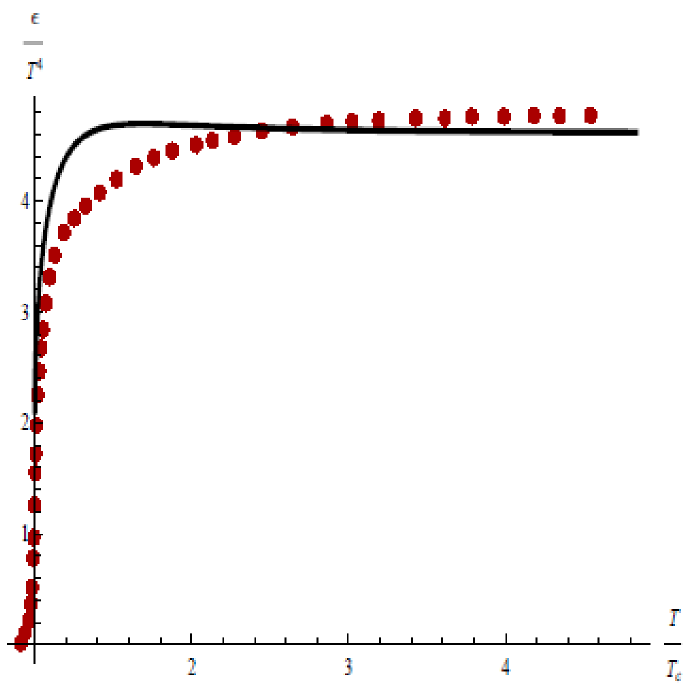
$$T_c = 201\text{MeV}$$

D.N. Li, S. He, M.H., Q. S. Yan, arXiv:1103.5389, JHEP2011

$$\frac{dp(T)}{dT} = s(T).$$

$$\epsilon = -p + sT.$$

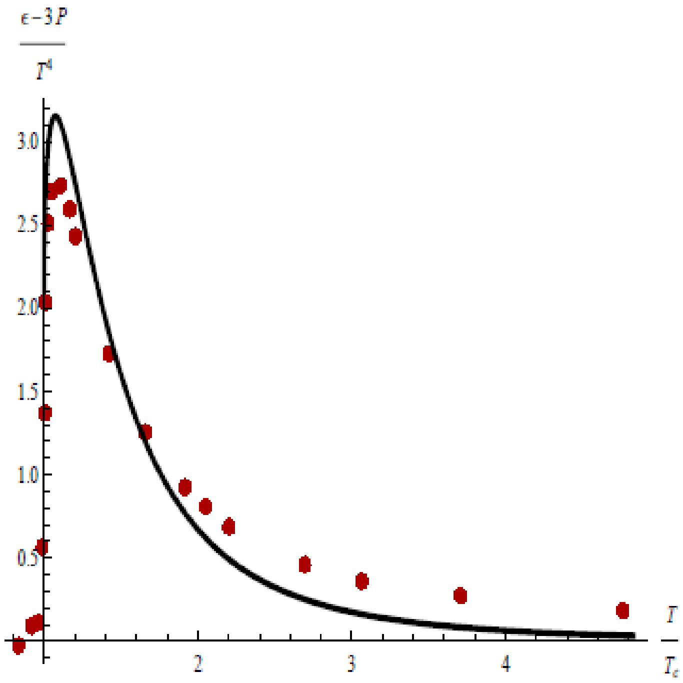


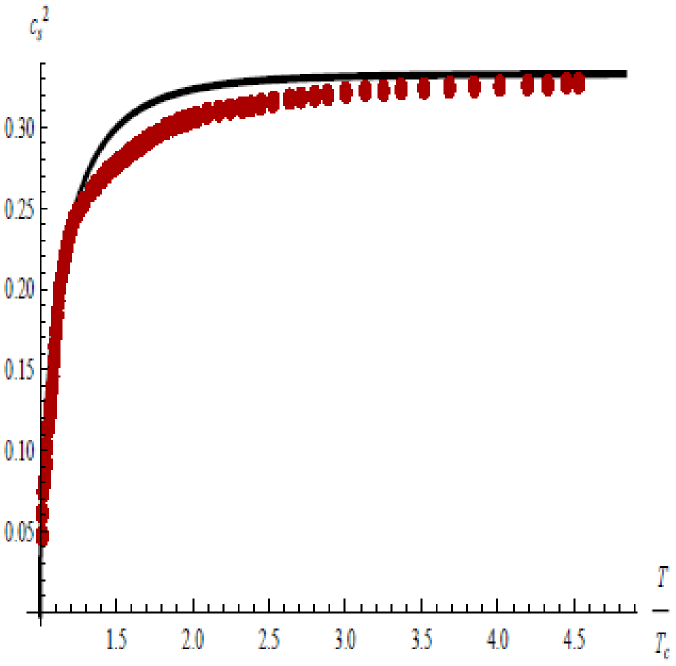


D.N. Li, S. He, M.H., Q. S. Yan, arXiv:1103.5389, JHEP2011

Trace anomaly

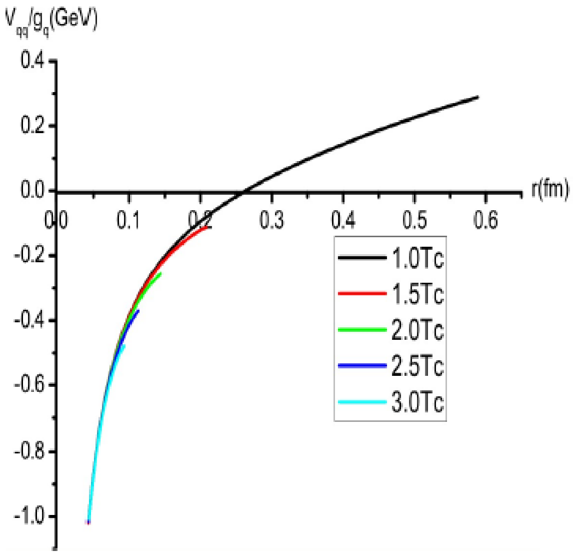
$$c_s^2 = \frac{d \log T}{d \log s} = \frac{s}{T ds/dT},$$



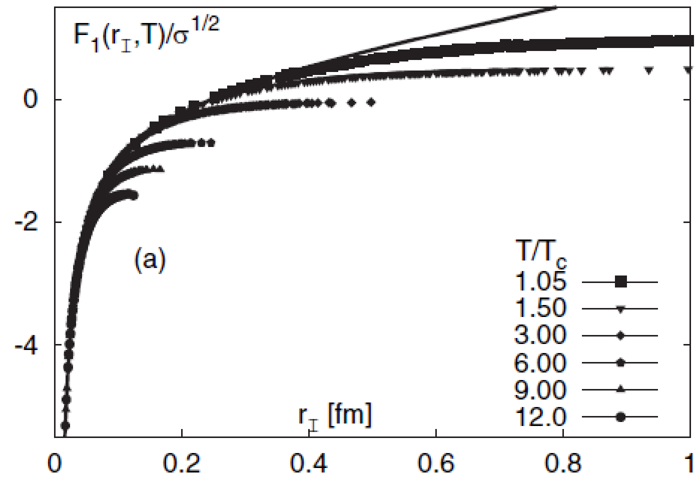


D.N. Li, S. He, M.H., Q. S. Yan, arXiv:1103.5389, JHEP2011

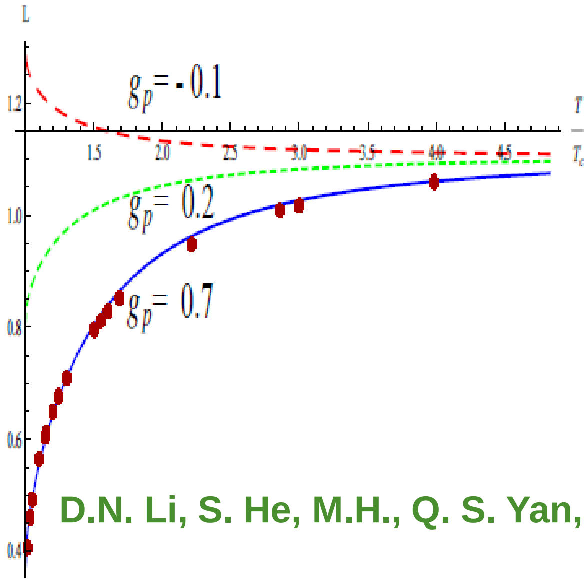
Electric screening



Heavy quark potential

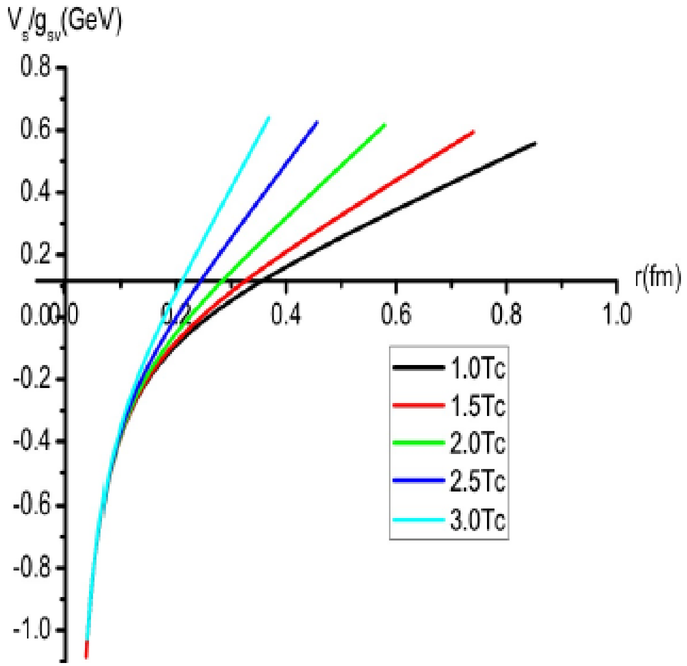


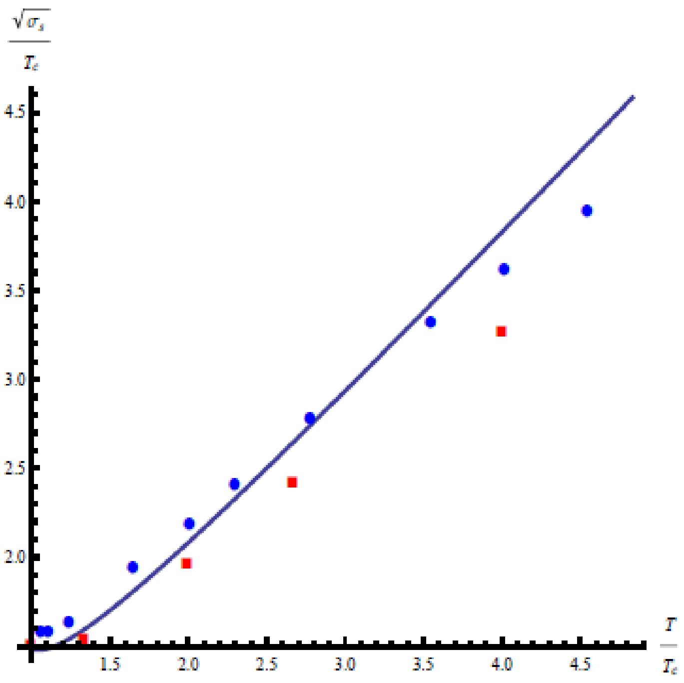
Polyakov loop: color electric deconfinement



D.N. Li, S. He, M.H., Q. S. Yan, arXiv:1103.5389, JHEP2011

Magnetic screening and magnetic confinement





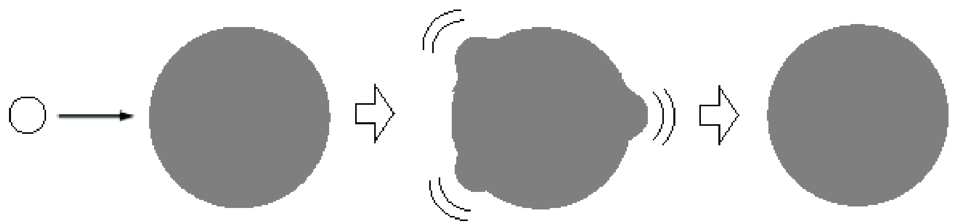
spatial Wilson loop spatial string tension

D.N. Li, S. He, M.H., Q. S. Yan, arXiv:1103.5389, JHEP2011

Transport properties

shear/bulk viscosity,
Jet quenching parameter

Shear viscosity from AdS/CFT



shear viscosity ⇔ absorption cross section of graviton

$$\eta = \pi N^2 T^3 / 8$$

entropy ⇔ horizon area

$$s = \pi^2 N^2 T^3 / 2$$

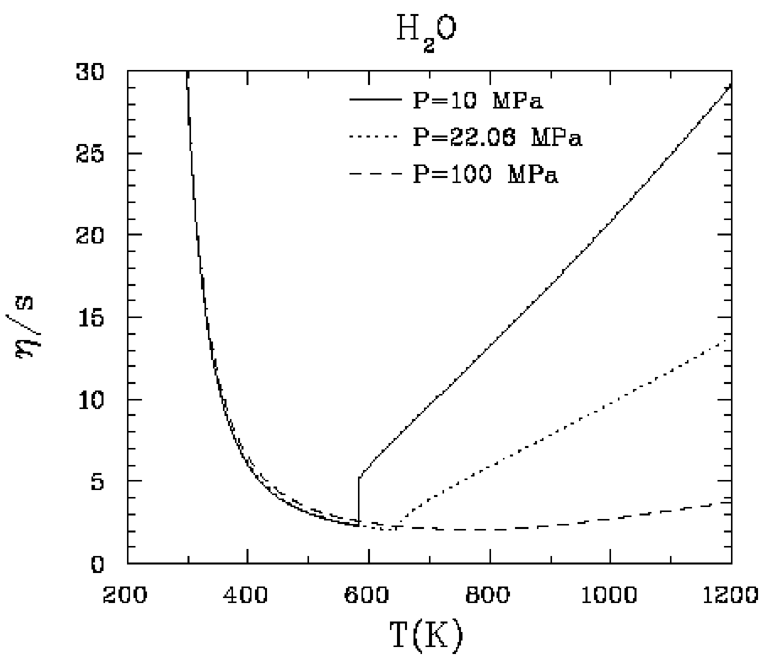
$$\frac{\eta}{s} = \frac{1}{4\pi}$$

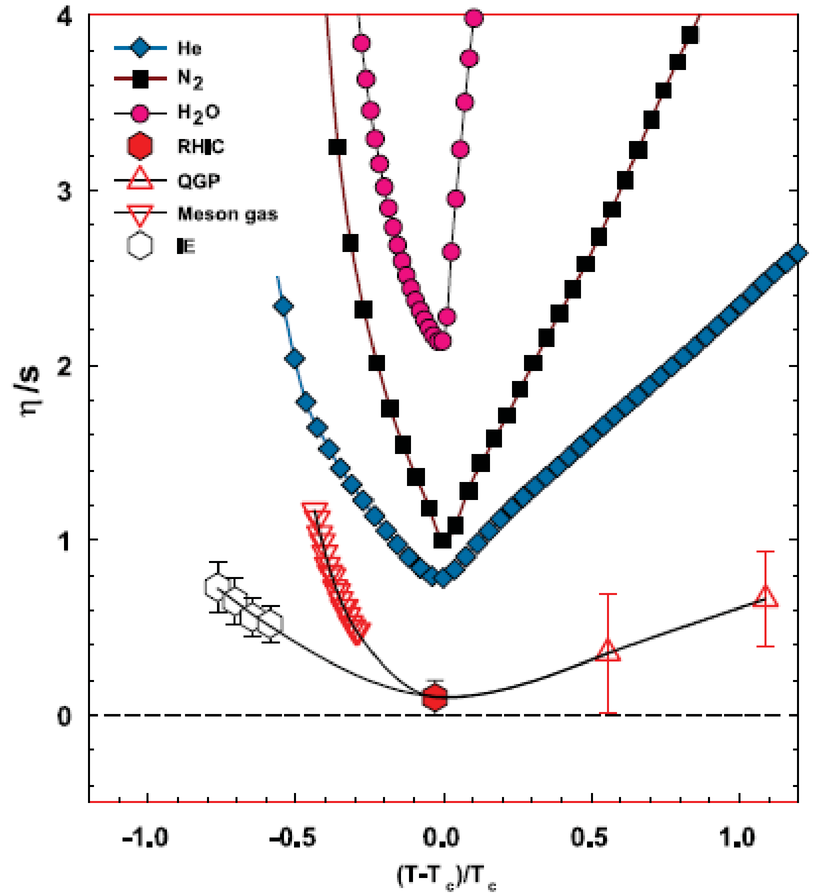
Minimum bound?

Kovtun - Son - Starinets (2004)

Shear viscosity over entropy density:

minimum near phase transition

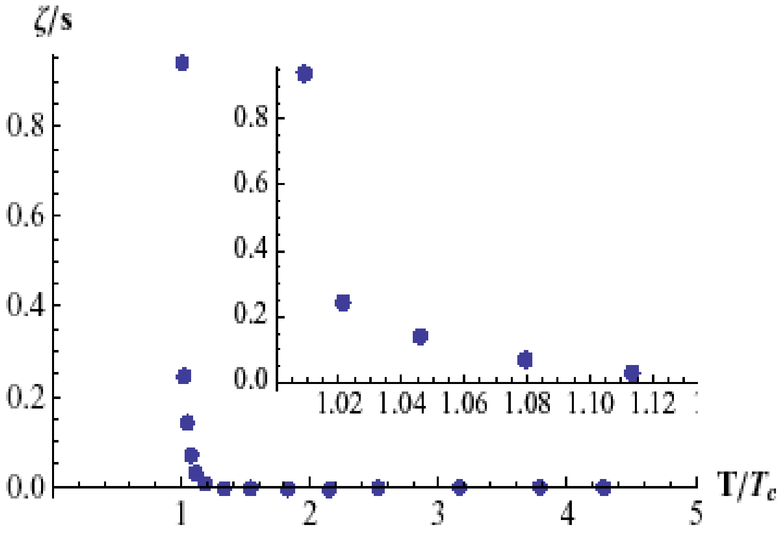




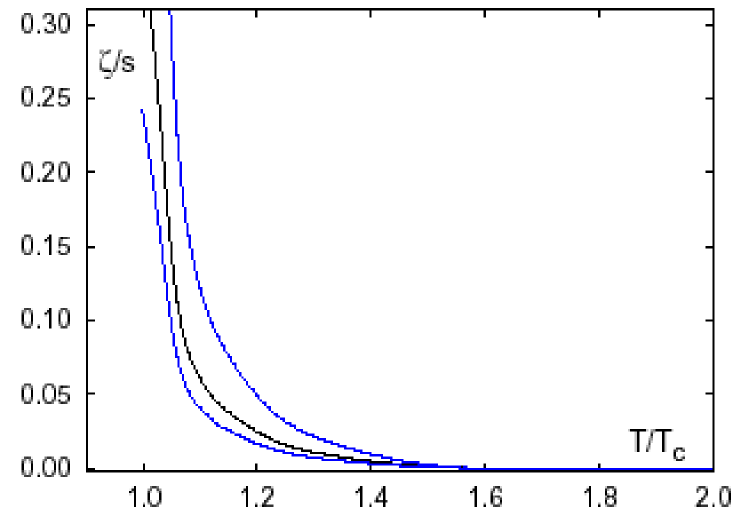
Csernai et.al. Phys.Rev.Lett.97:152303,2006

Lacey et al., PRL 98:092301,2007

Bulk viscosity over entropy density: LQCD
sharply rising near phase transition



Pure gluodynamics



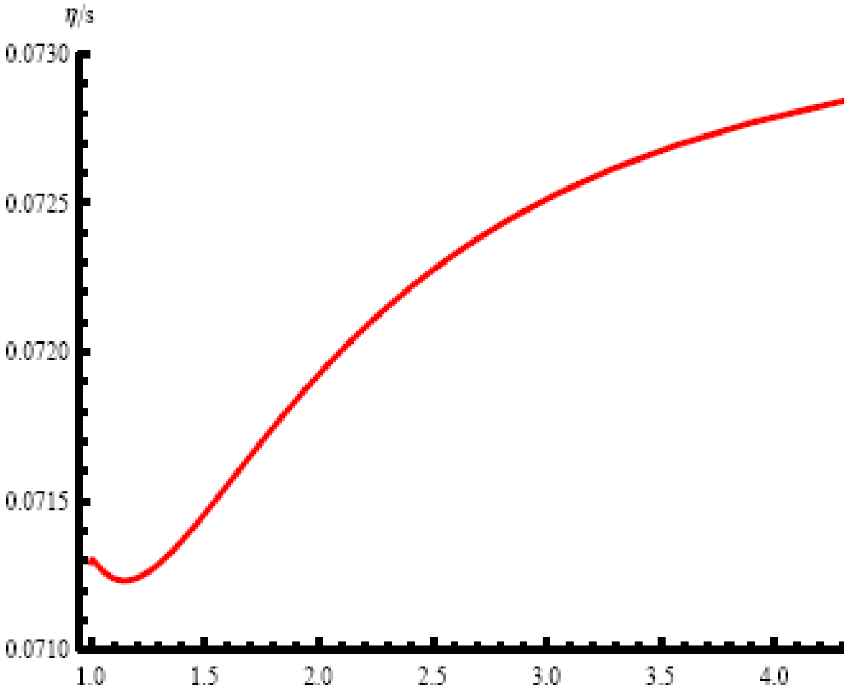
2-flavor case

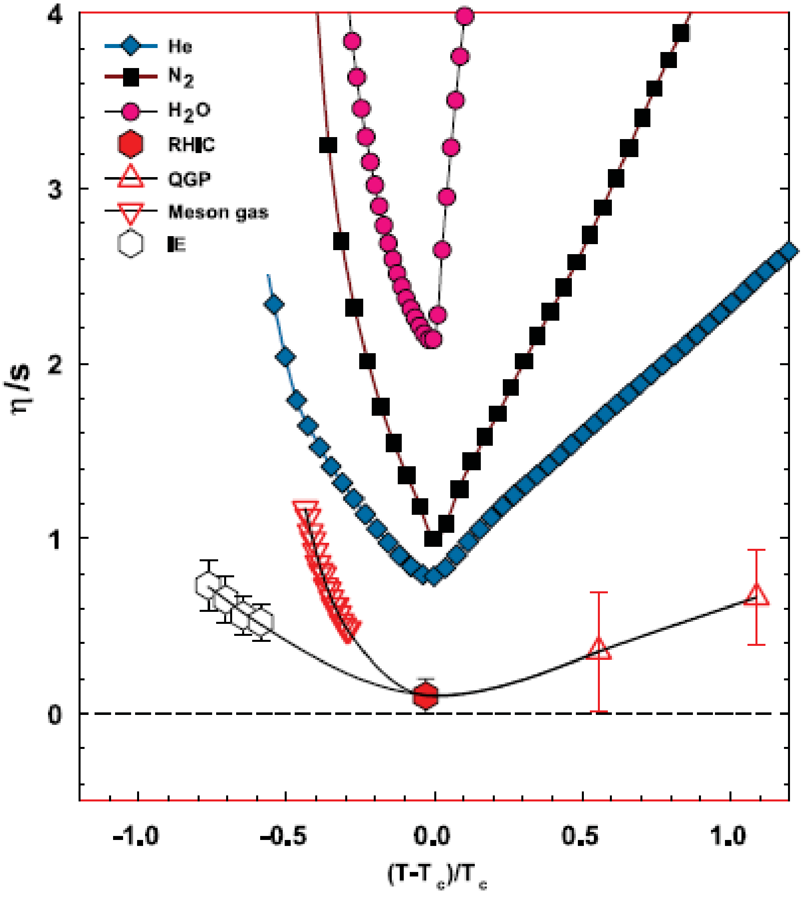
$$\zeta = \frac{1}{9\,\omega_0}\left\{T^5 \frac{\partial}{\partial T}\frac{(\epsilon_T - 3p_T)}{T^4} + 16|\epsilon_v|\right\}$$

Dmitri Kharzeev, Kirill Tuchin arXiv:0705.4280 [hep-ph],
F.Karsch, Dmitri Kharzeev, Kirill Tuchin arXiv:0711.0914 [hep-ph],
Harvey Meyer arXiv:0710.3717 [hep-ph],

Shear viscosity from dynamical hQCD

$$S = \frac{1}{16\,\pi G_5}\int d^5x\,\sqrt{-g}\left[R - \frac{4}{3}(\nabla\phi)^2 + V(\phi) + \ell^2\,\beta\,e^{\sqrt{\frac{2}{3}}\,\gamma\,\phi}\,R_{\mu\nu\lambda\rho}R^{\mu\nu\lambda\rho}\right]$$

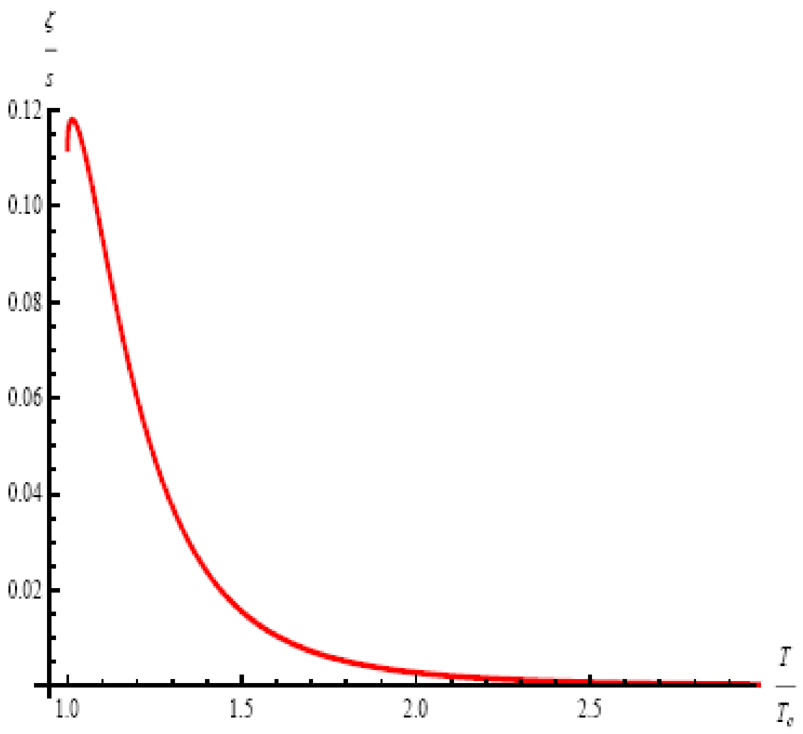


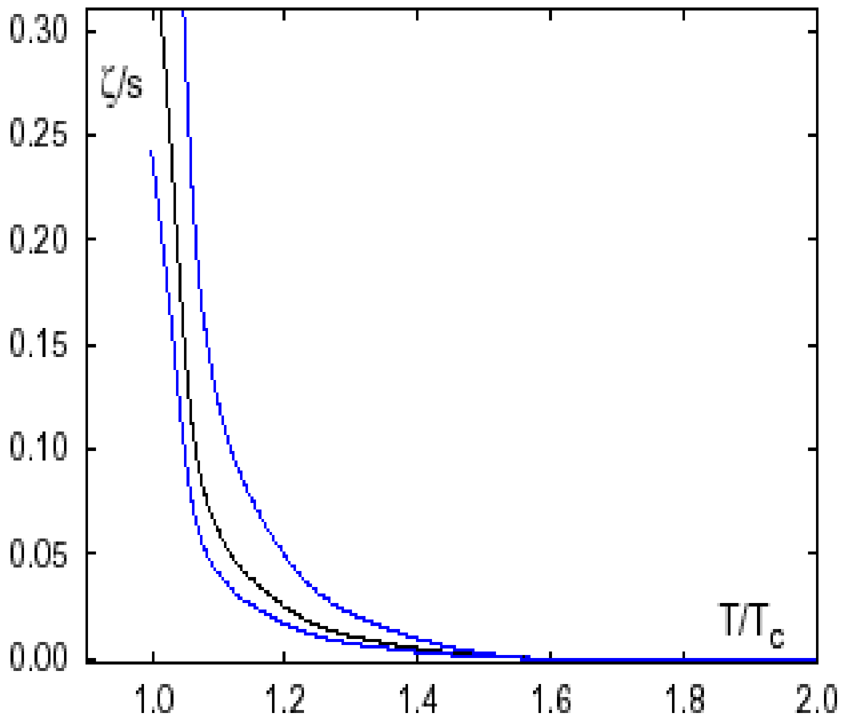


Danning Li, Song He, M.H. JHEP2015

Lacey et al., PRL 98:092301,2007

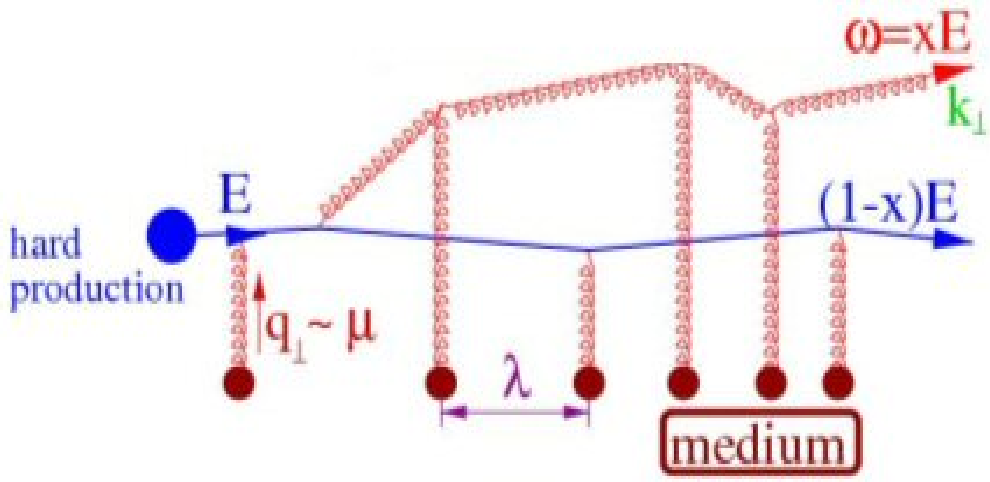
Bulk viscosity from dynamical hQCD

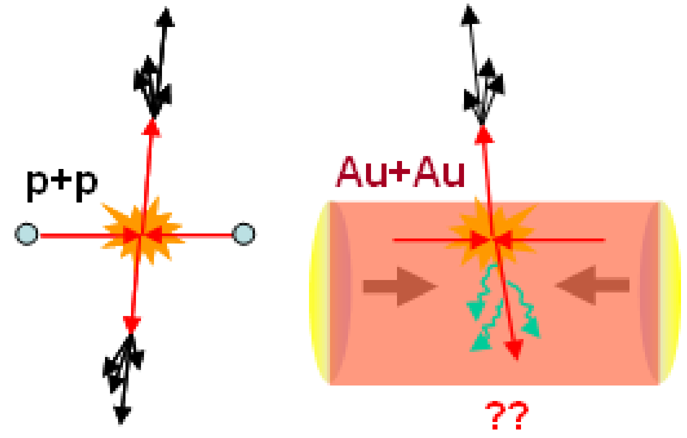




Danning Li, Song He, M.H. JHEP2015 Dmitri Kharzeev, Kirill Tuchin arXiv:0705.4280,

Jet quenching parameter





$$\Delta E \approx -\frac{\alpha_S}{2\pi} N_C \, \hat{q} \, L^2$$

Baier, Dokshitzer, Mueller, Peigne, Schiff (1996):

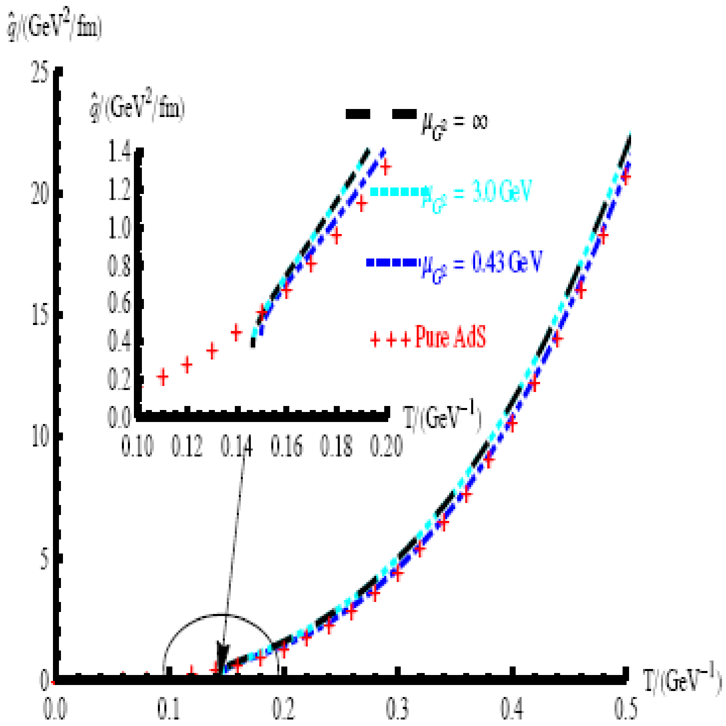
$\hat{q}$: reflects the ability of the medium to "quench" jets.

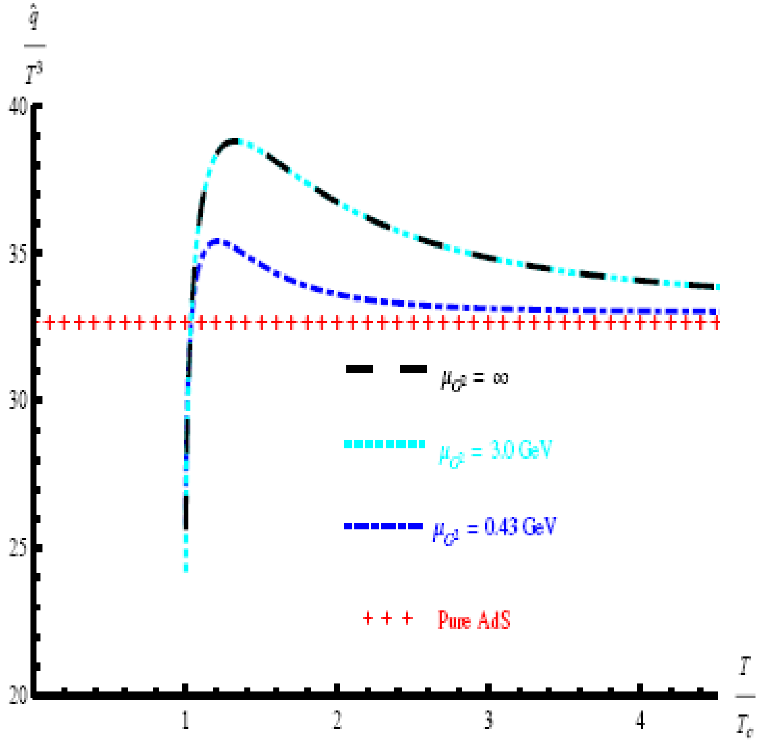
$$\hat{q} = \frac{\langle k_T^2 \rangle}{L} \approx \frac{\mu^2}{\lambda}$$

μ : Debye mass λ : mean free path

Jet quenching from dynamical hQCD

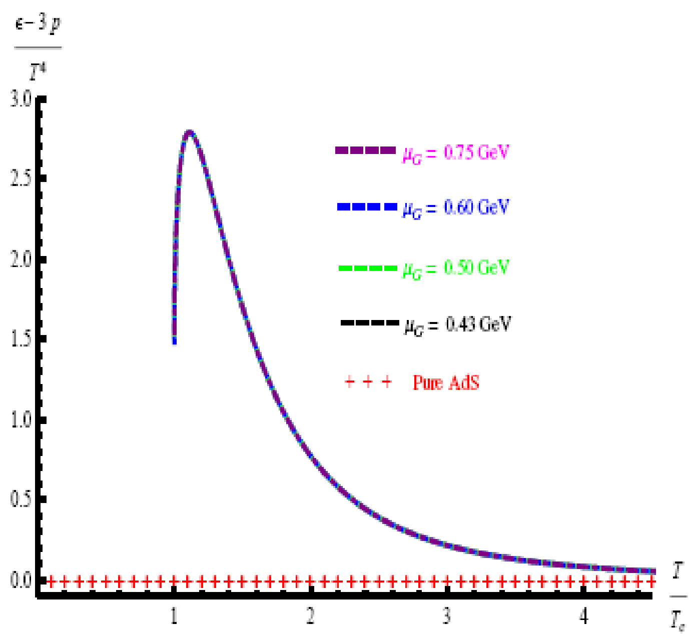
Danning Li, Jinfeng Liao, M.H. PRD2014

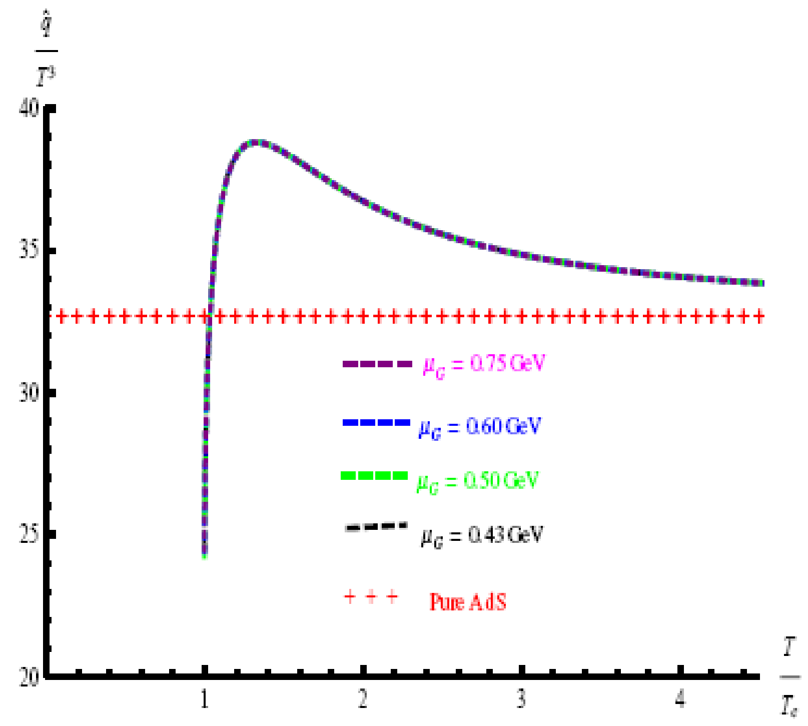




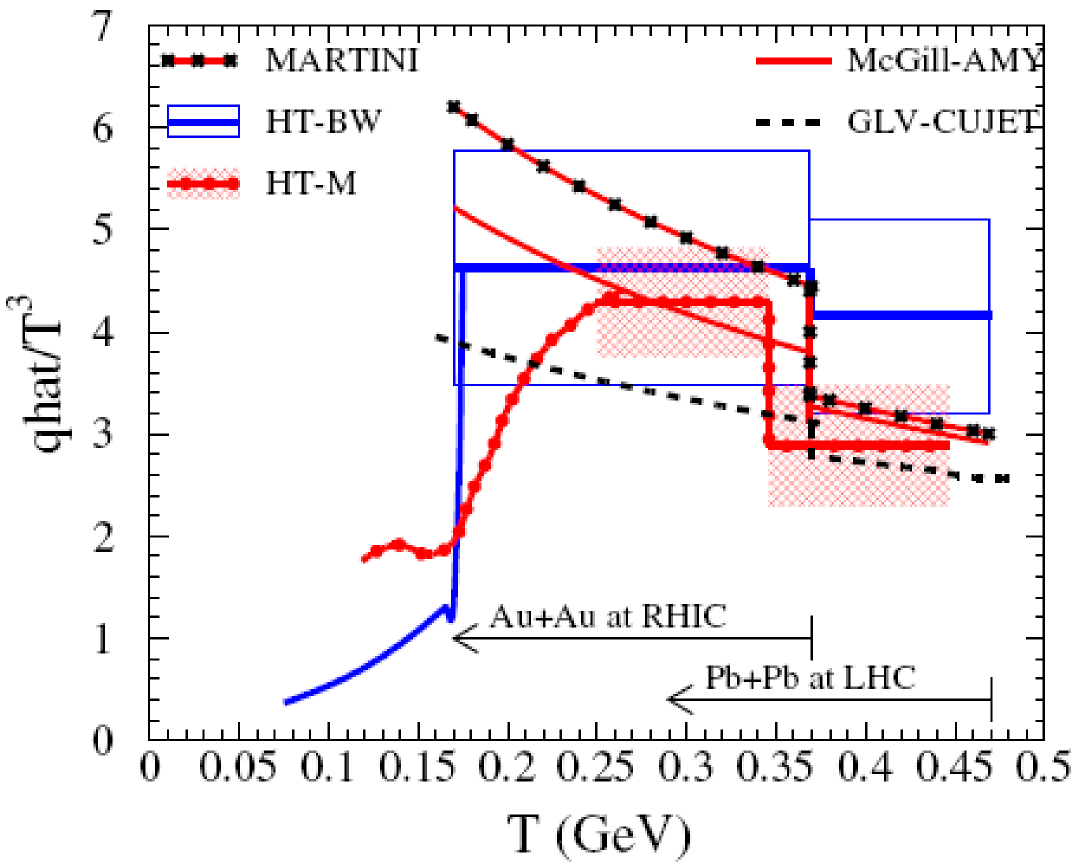
Jet quenching characterizing phase transition!

Danning Li, Jinfeng Liao, M.H. PRD2014





Temperature dependence of jet quenching parameter [Jet Collaboration] arXiv:1312.5003



IV. Realization of chiral symmetry breaking & restoration

First time in holographic QCD model

K. Chelabi, Z.Fang, M.Huang, D.N.Li, Y.L.Wu,
arXiv:1511.02721, 1512.06493

Only focus on the scalar sector:

$$SU(N_f)_L \times SU(N_f)_R$$

$$S = -\int d^5x \sqrt{-g} e^{-\Phi} Tr(D_m X^+ D^m X + V_X(|X|)).$$

$$ds^2 = e^{2A_s(z)}(-f(z)dt^2 + \frac{1}{f(z)}dz^2 + dx_i dx^i),$$

$$A_s(z) = -\log(z),$$

$$f(z) = 1 - \frac{z^4}{z_h^4}.$$

$$S_\chi = -\int d^5x\sqrt{-g}e^{-\Phi}(\frac{1}{2}g^{zz}\chi'^2 + V(\chi)),$$

$$X_0 = \frac{\chi(z)}{\sqrt{2N_f}} I_{N_f}$$

Profile of the scalar potential

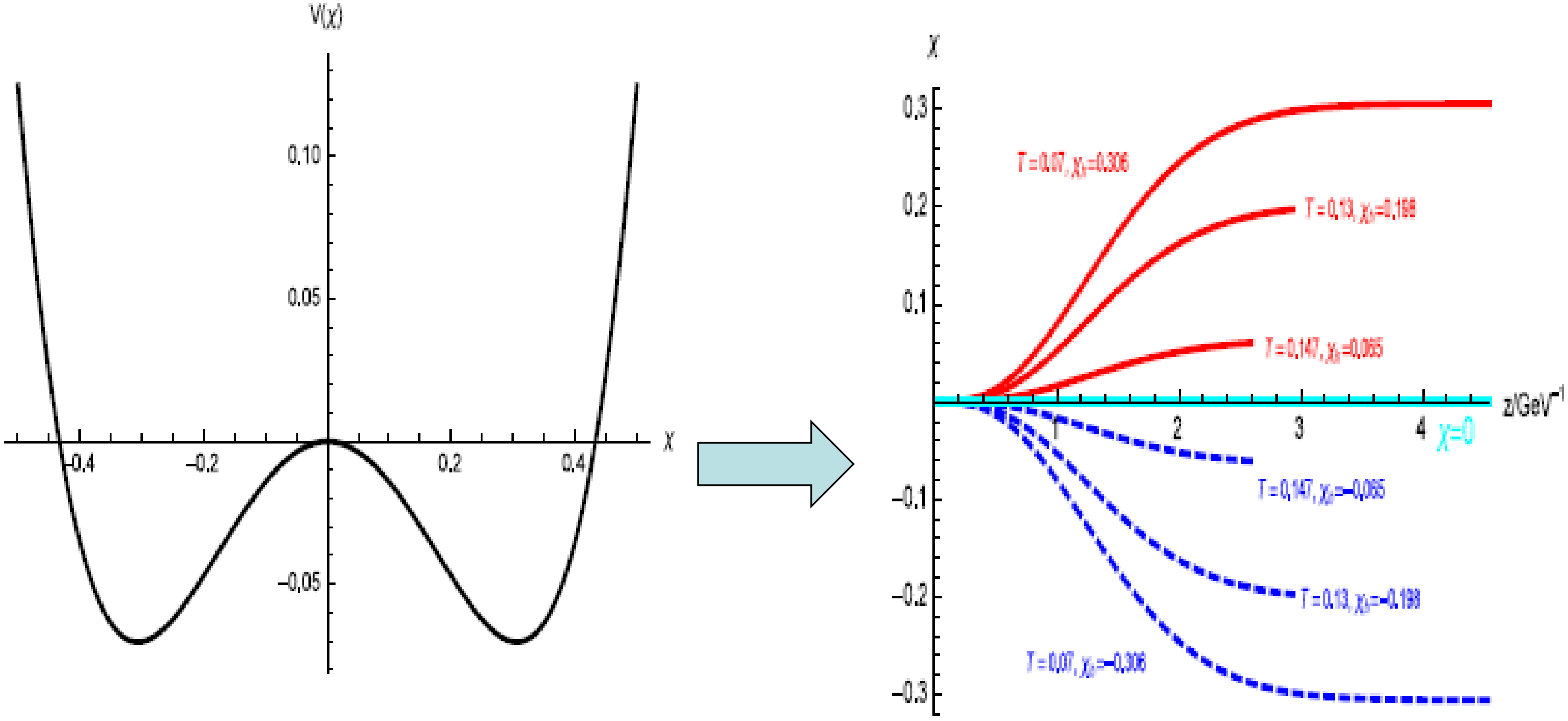
$$V(\chi) \equiv Tr(V_X(|X|)) = -\frac{3}{2}\chi^2 + v_3\chi^3 + v_4\chi^4.$$

Only for three-flavor scalar

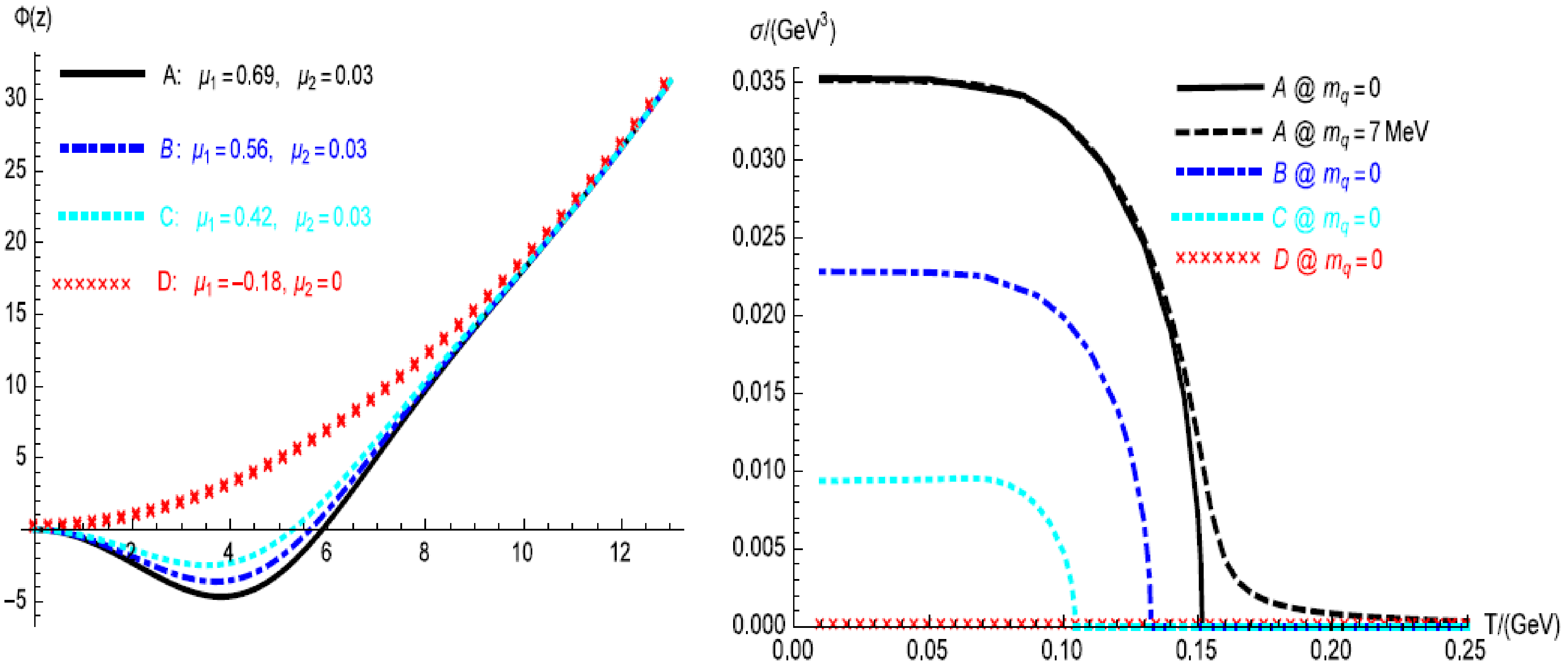
Profile of the dilaton field

$$\Phi(z) = -\mu_1 z^2 + (\mu_1 + \mu_0) z^2 \tanh(\mu_2 z^2),$$

Profile of the scalar potential determines the possible solution of the chiral condensate



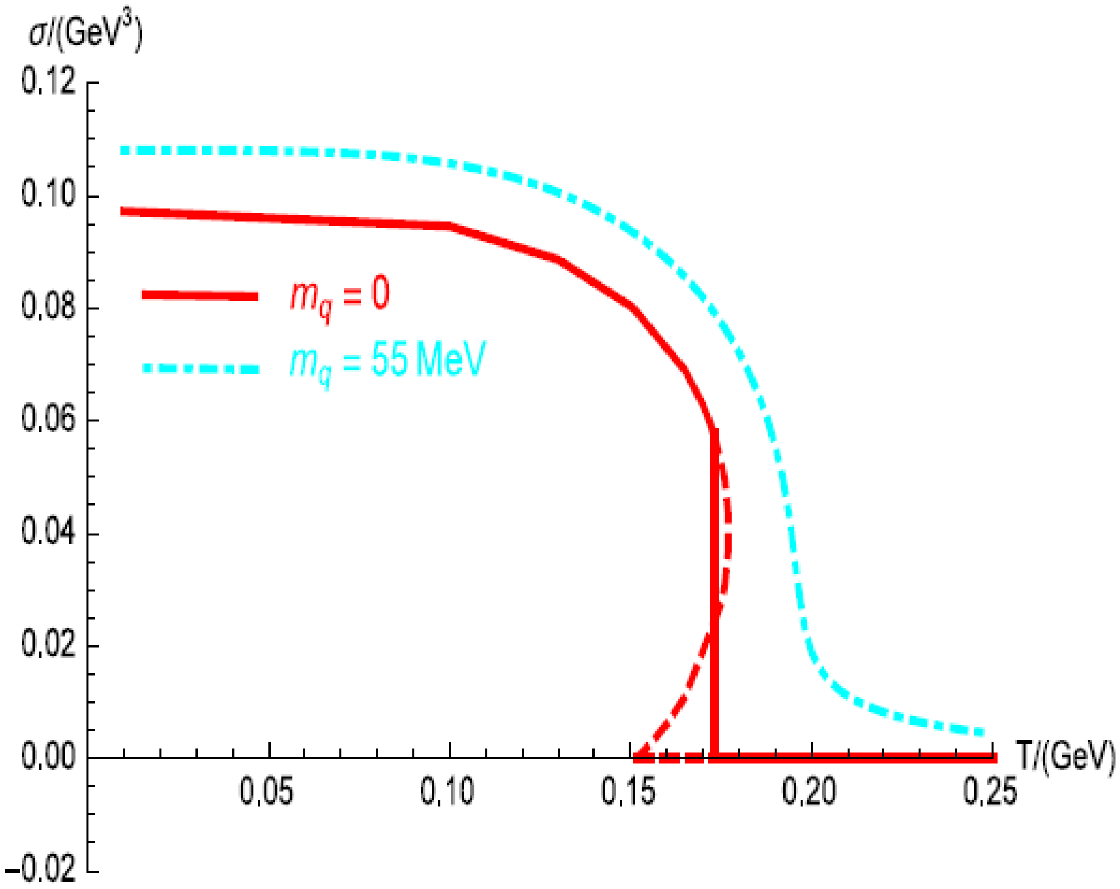
Profile of the dilaton field represents the gluodynamics, and it determines the real solution of the chiral condensate



Two-flavor case:

chiral limit, 2nd order phase transition

nonzero current quark mass, cross-over



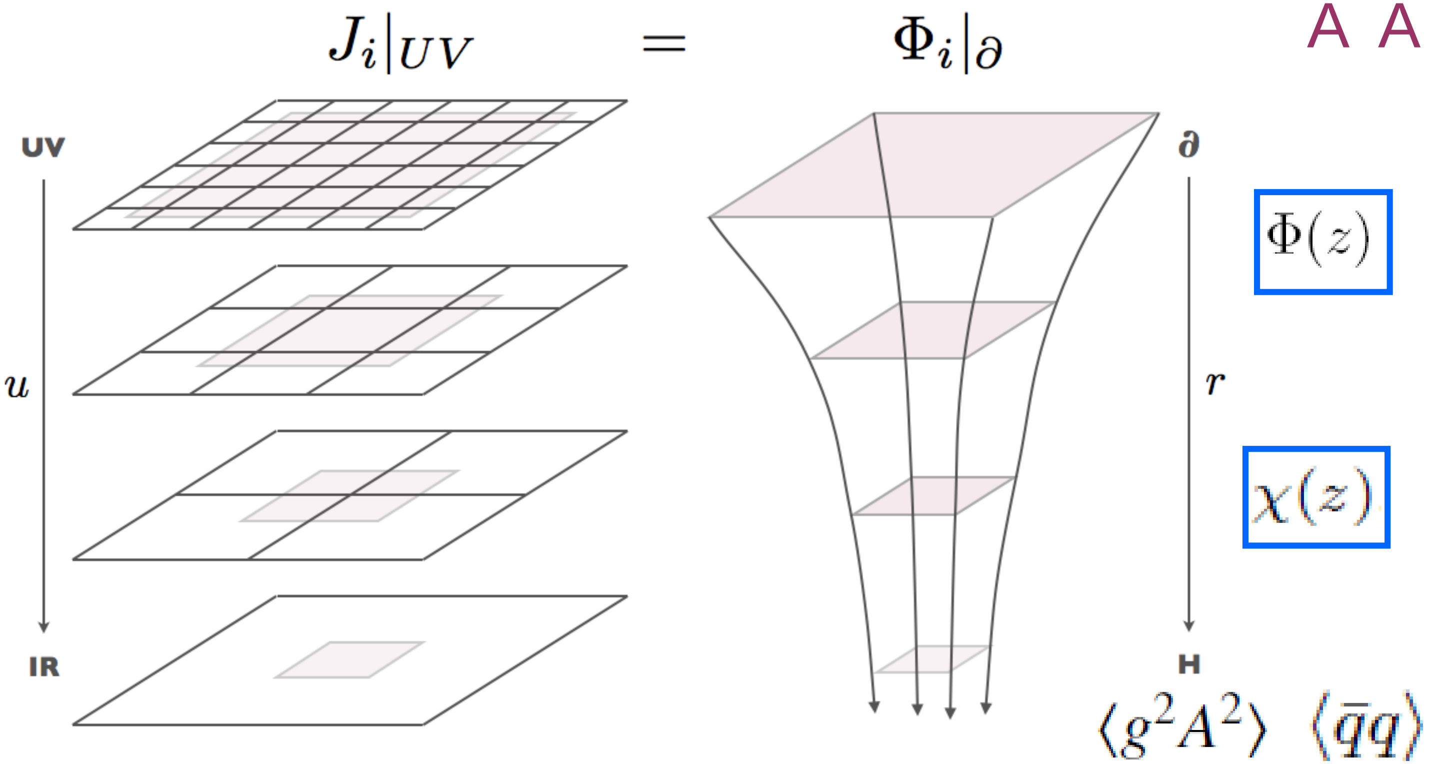
Three-flavor case:

chiral limit, 1st order phase transition

finite current quark mass, cross-over

V. Conclusion and discussion

A AdS_5



From UV to IR

5D effective QCD: Correct gluon dynamics and chiral dynamics running from UV to IR gives correct physics!

In the DhQCD model, we have achieved:

1, QCD vacuum properties

glueball spectra, light-flavor meson spectra,

chiral symmetry breaking and linear confinement

2, QCD phase transitions

deconfinement phase transition

chiral phase transition

3, Equation of state for QCD matter

4, Transport properties for QCD matter

5D effective QCD model is more powerful than 4D effective QCD model!

For the future

CEP, unique signal for CEP?
2^{nd} order transport properties?

Heavy flavor Hadron spectra?
Exotic states?
PDF?

Thanks for your attention!