Dynamical holographic QCD model for hadron spectra and sQGP

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Content

I. Dynamical hQCD model

II. Hadron spectra

Glueball, light-flavor meson spectra

III. sQGP

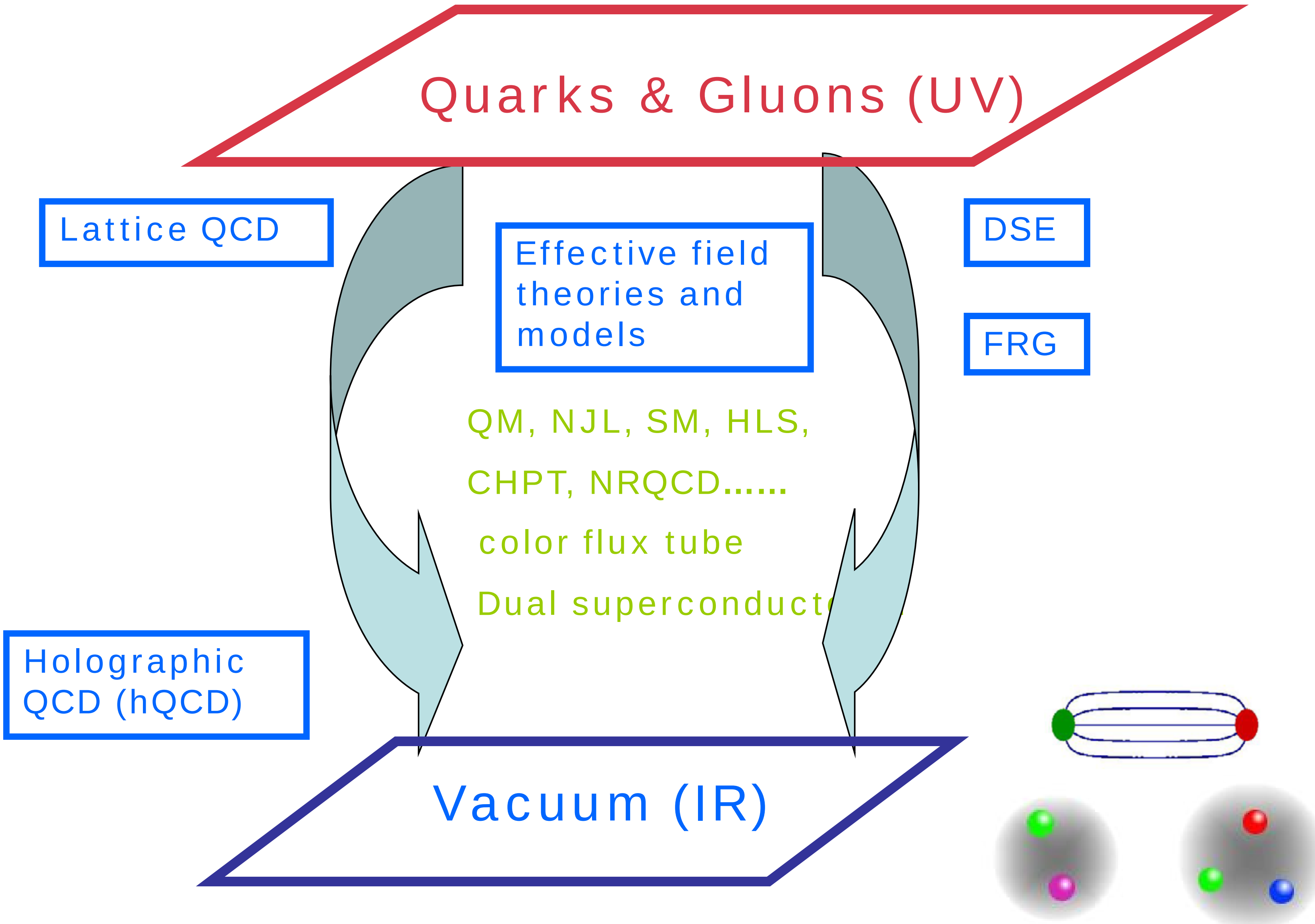
Equation of state, transport properties

IV. Chiral phase transition

V. Conclusion and discussion

I. Dynamical hQCD model

Strong QCD



Quarks & Gluons (UV)
Lattice QCD
Effective field theories and models
DSE
FRG
QM, NJL, SM, HLS,
CHPT, NRQCD……
color flux tube
Dual superconduct
Holographic QCD (hQCD)
Vacuum (IR)

Holographic Duality: Gravity/QFT

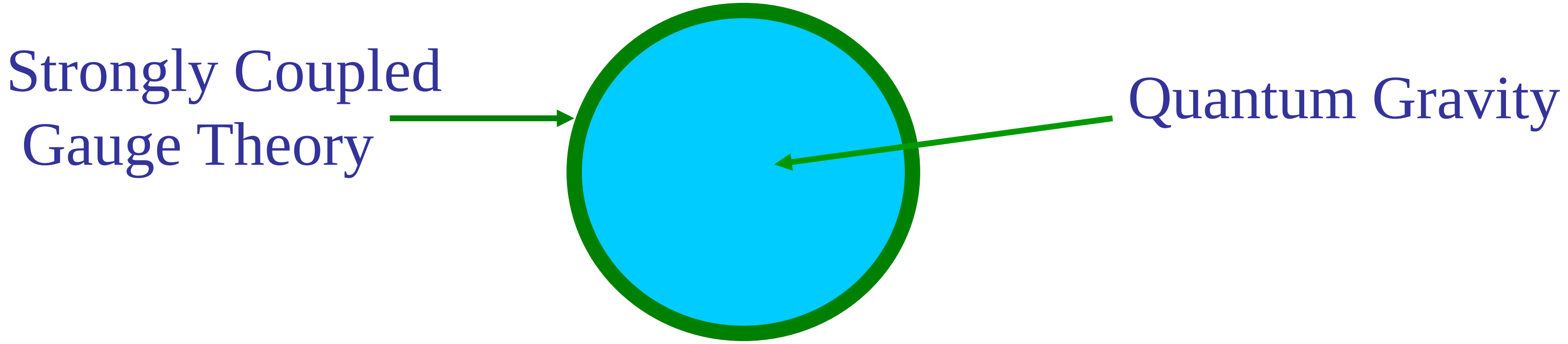
AdS/CFT : Original discovery of duality

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.

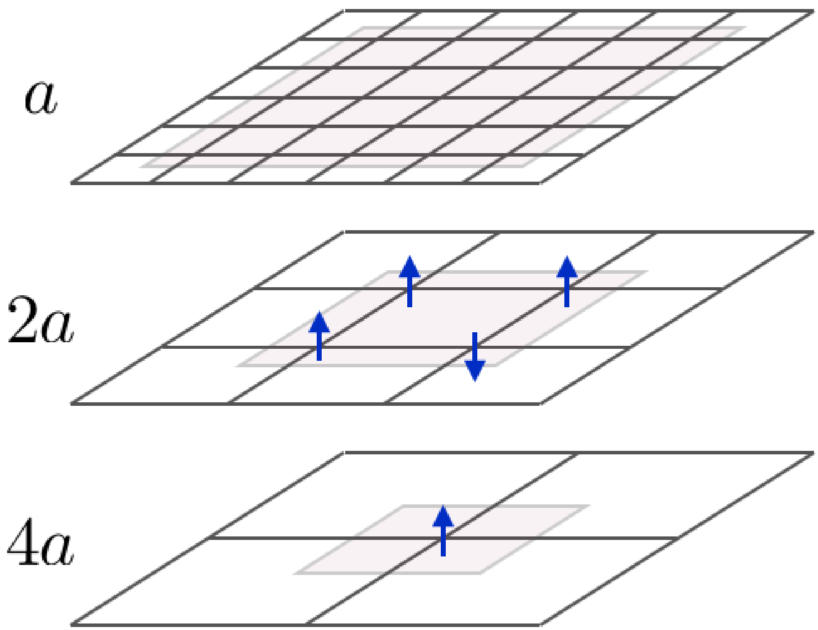
arXiv:1205.5180

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

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



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

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

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

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

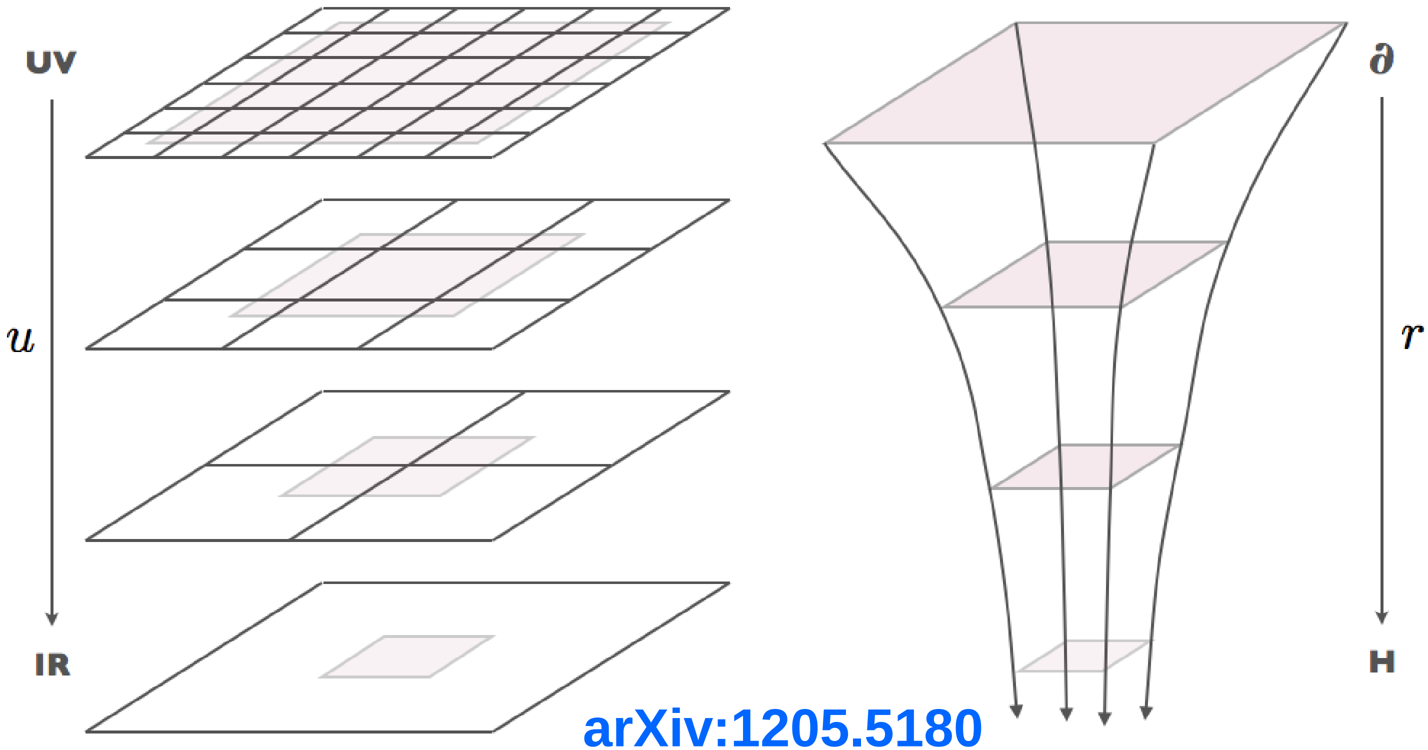
arXiv:1205.5180

Holographic Duality & RG flow

QFT on lattice equivalent to GR problem from Gravity

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

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



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

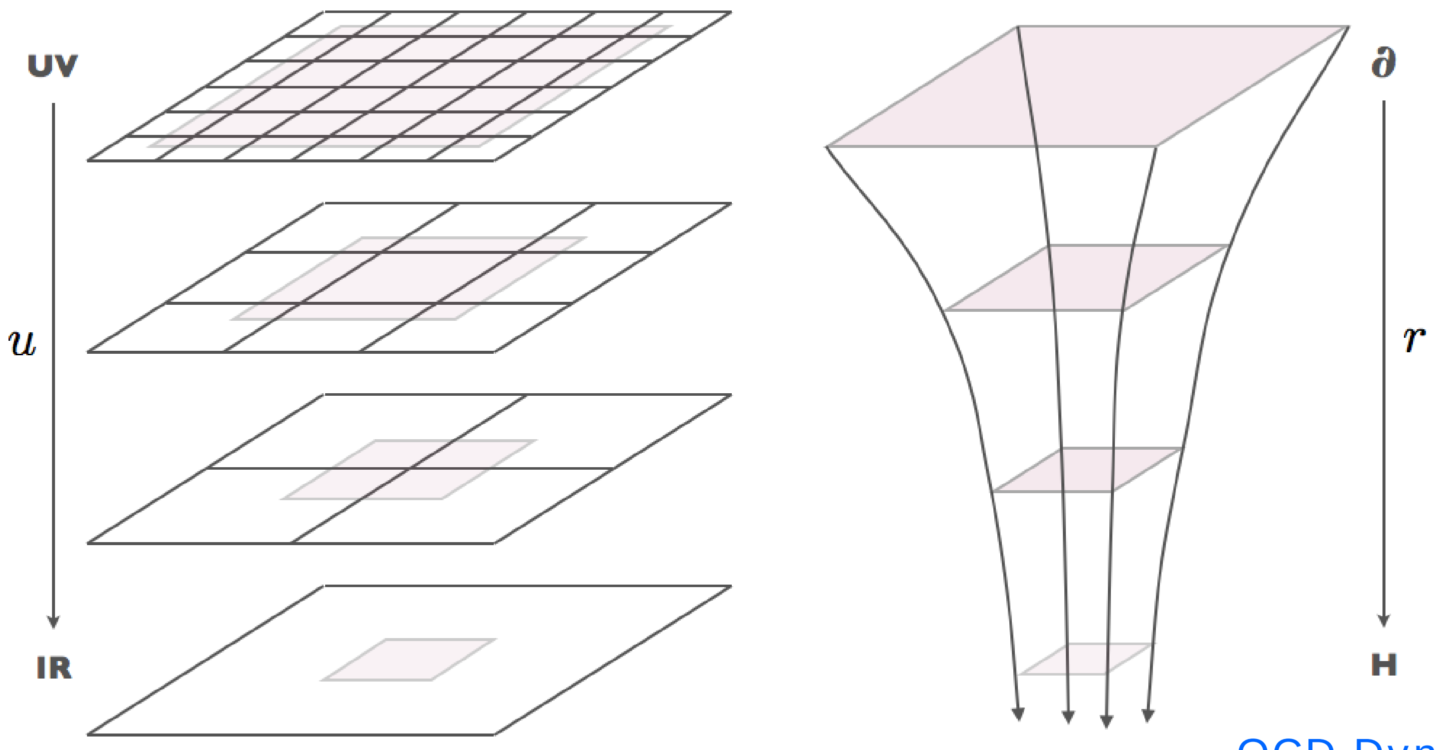
Input: QCD dynamics at IR

Solve: Metric structure, dilaton potential

Dynamical hQCD & RG

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

A AdS_5



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

Glueball spectra

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

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

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

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

Pure gluon system:

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

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

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

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

5D action: graviton-dilaton

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

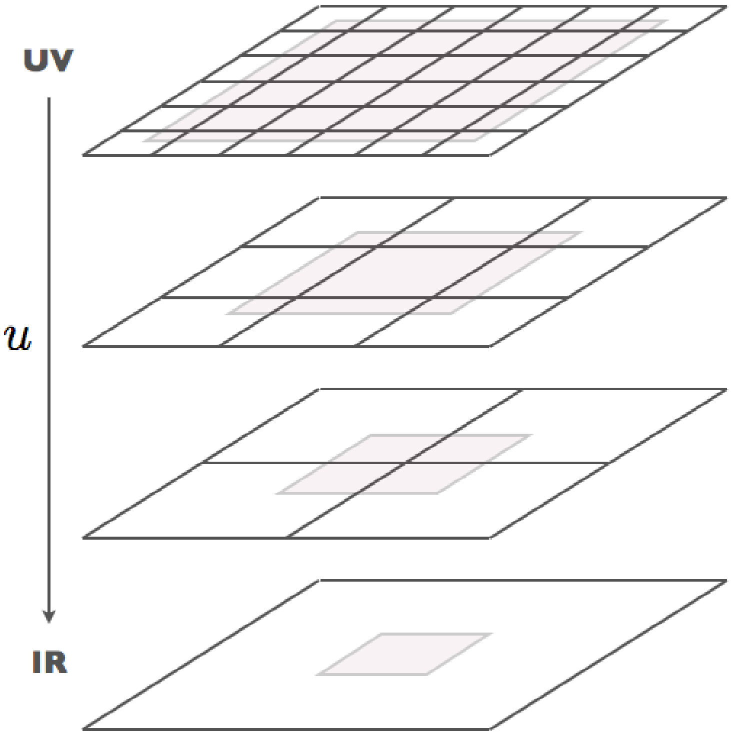
$\mathrm{Tr}\langle G^2 \rangle$ $\langle g^2 A^2 \rangle$ dual to $\Phi(z)$

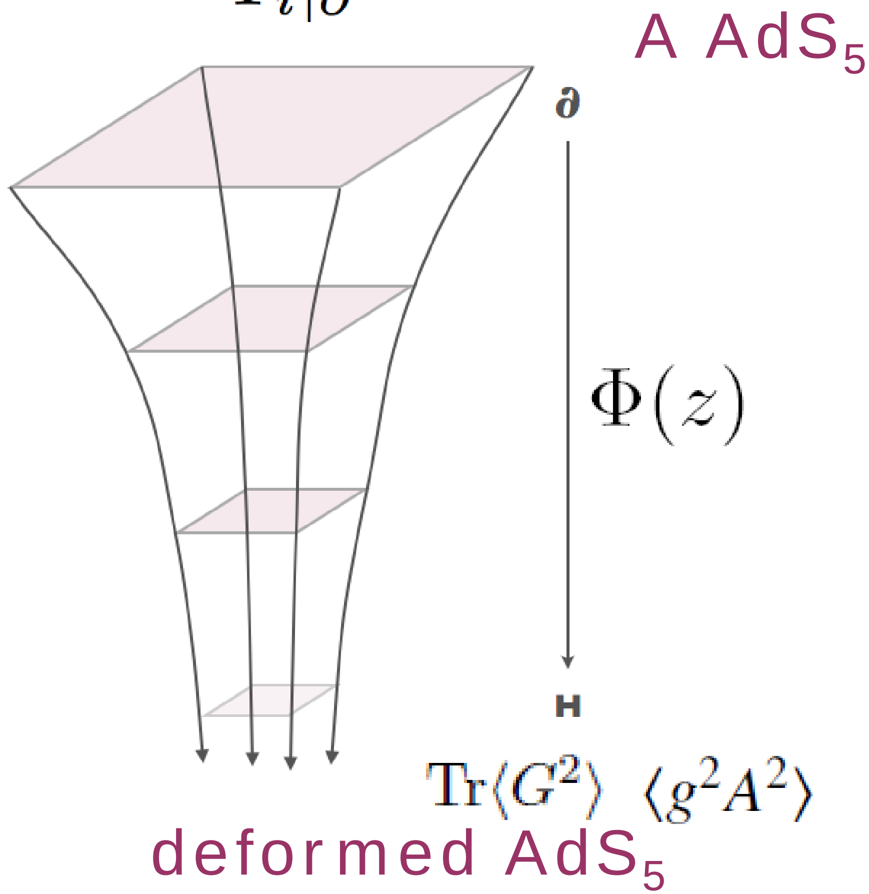
$$\Phi(z) = \mu_G^2 z^2 \tanh(\mu_{G^2}^4 z^2 / \mu_G^2)$$

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

Graviton-dilaton system

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





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

Scalar glueball

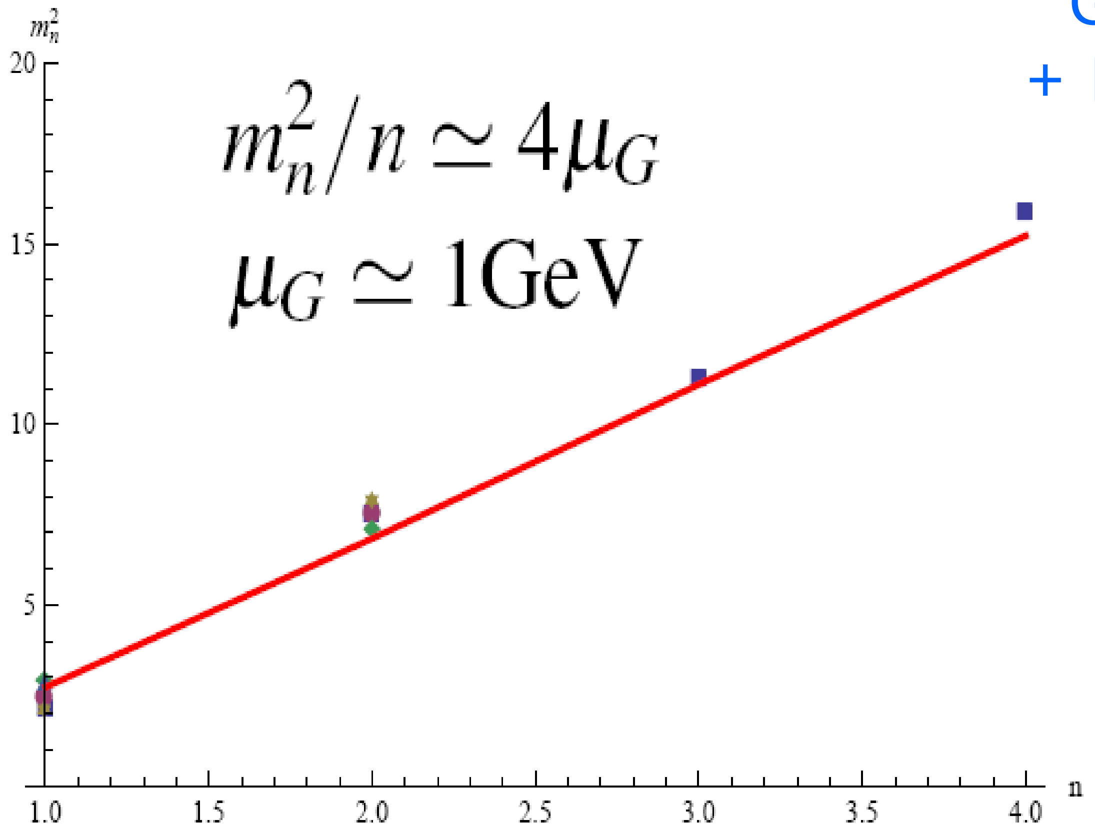
$$S_{\mathscr{G}} = \int d^5x \sqrt{g_s} \frac{1}{2} e^{-\Phi} [\partial_M \mathscr{G} \partial^M \mathscr{G} + M^2_{\mathscr{G},5} \mathscr{G}^2]$$

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

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

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

Glueball

Yidian Chen, M.H., arXiv: 1511.07018

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

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

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

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

$M^2_5(z) = M^2_5 e^{-2\Phi/3}$, $p = 1$ for even parity and $p = -1$ for odd parity.

Glueball

Yidian Chen, M.H., arXiv: 1511.07018

EOM:

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

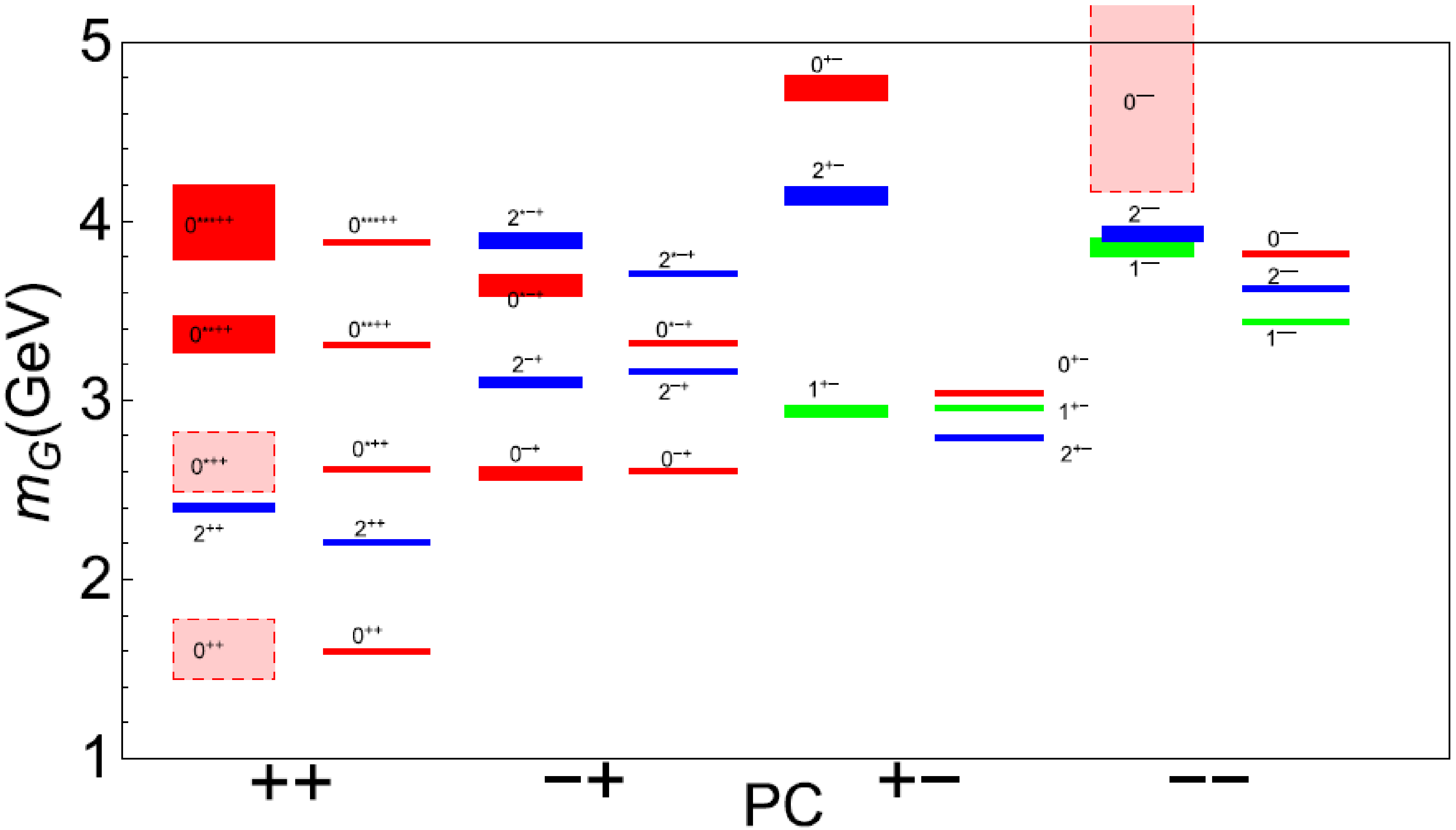
$$V_{\mathscr{A}} = \frac{cA_s'' - p\Phi''}{2} + \frac{(cA_s' - p\Phi')^2}{4} + e^{2A_s - \frac{2}{3}\Phi} M^2_{\mathscr{A},5},$$

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 glueball0^{--} , 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

Glueball spectra: Yidian Chen, M.H., arXiv: 1511.07018

Trigluon glueball spectra agree with 1st version QCDSR result

J^{PC}	Lattice QCD	Flux tube model	QCDSR	MDSM
0^{--}	5.1661GeV	2.79GeV	3.81, 4.33GeV	3.817GeV
2^{+-}	4.14GeV	X	2.77, 4.41, 4.99GeV	2.786GeV

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].

but … 2nd version, the updated 2^{+-} mass from QCDSM updated to 6.06 GeV

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 meson spectra

Light flavor meson spectra:

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

Action for pure gluon system: Graviton-dilaton coupling

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

Action for light hadrons: KKSS model

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

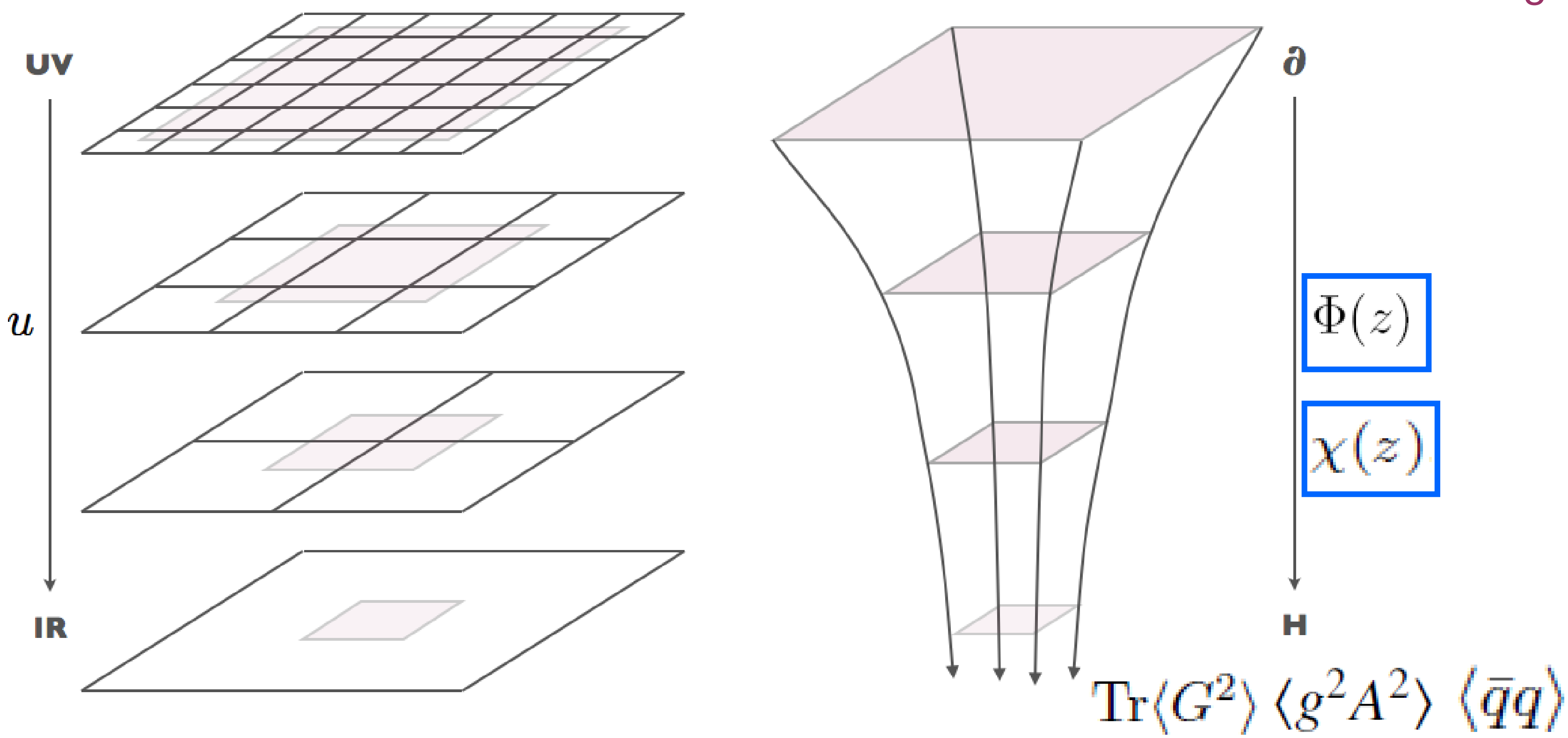
Total action:

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

Graviton-dilaton-scalar system

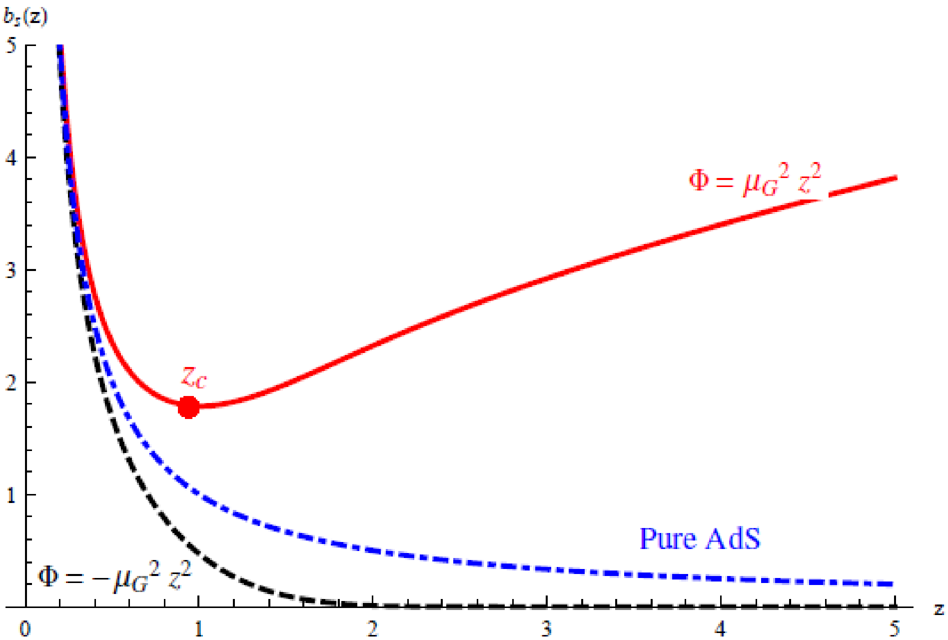
$$J_i|_{UV} = \Phi_i|_\partial$$

A AdS$_5$

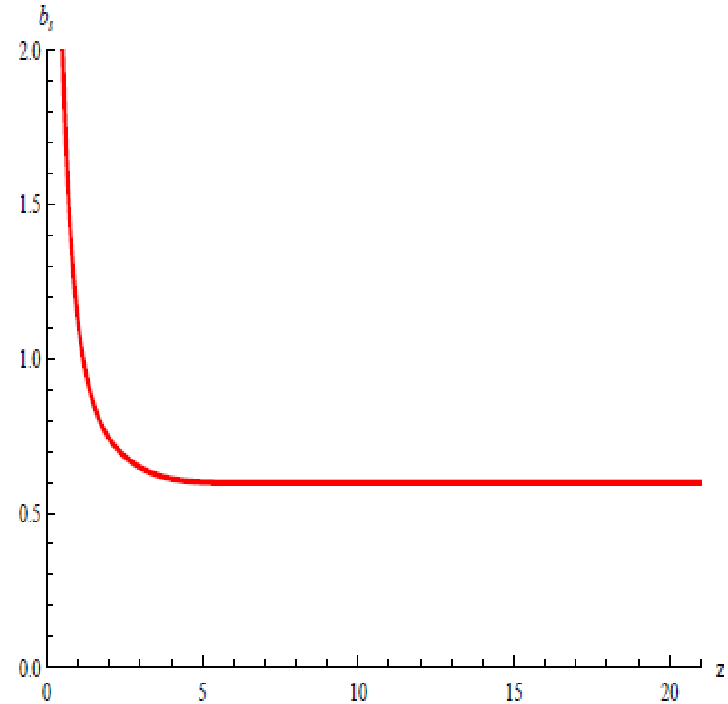


deformed AdS$_5$

quenched background



Unquenched background



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

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

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

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

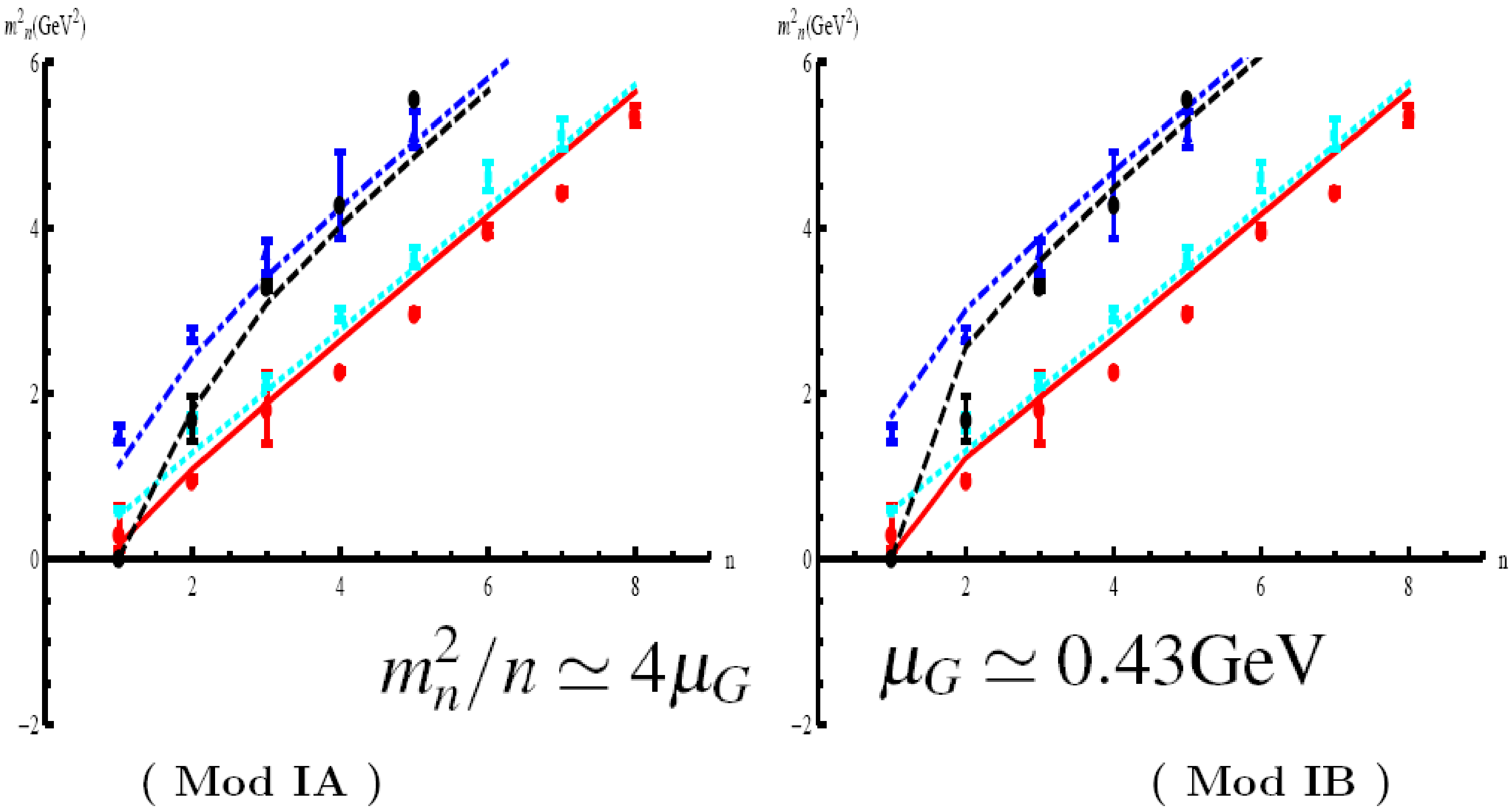
$$\textit{Dilaton in Mod II}: \quad \Phi(z) = \mu_G^2 z^2 \tanh(\mu_{G^2}^4 z^2/\mu_G^2)$$

	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

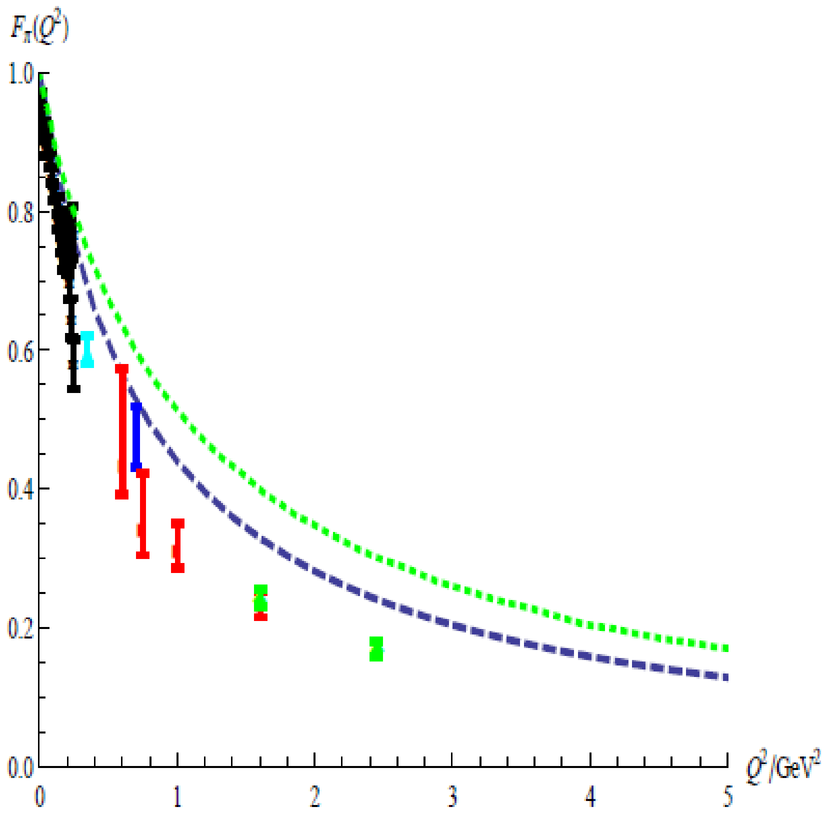
D.N. Li, M.H., JHEP2013, arXiv:1303.6929

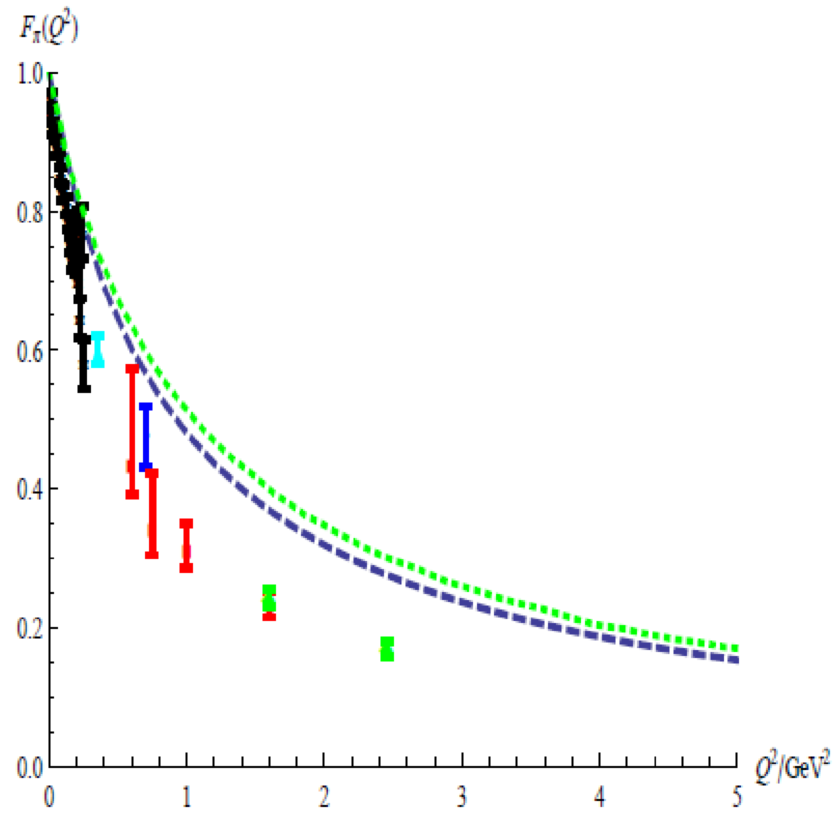


Ground states: chiral symmetry breaking
Excitation states: linear confinemnt

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.

$$\phi(z) = \phi_0 + \phi_1 \int_0^z \frac{e^{2A_s(x)}}{x^2}\, dx + \frac{3A_s(z)}{2}$$

$$+ \frac{3}{2}\int_0^z \frac{e^{2A_s(x)} \int_0^x y^2 e^{-2A_s(y)} A_s'(y)^2 dy}{x^2}\, dx,$$

$$f(z) = f_0 + f_1 \left(\int_0^z x^3 e^{2\phi(x) - 3A_s(x)}\, dx \right),$$

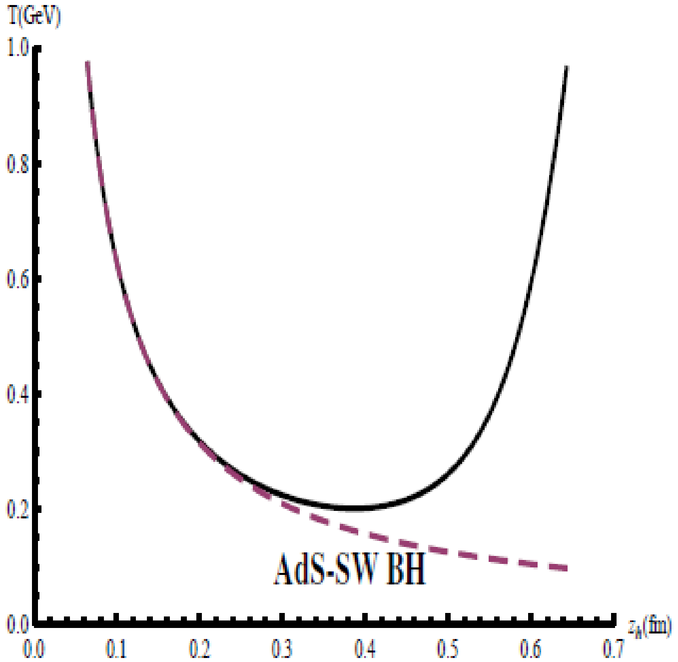
$$V_E(\phi) = \frac{e^{\frac{4\phi(z)}{3} - 2A_s(z)}}{L^2}$$

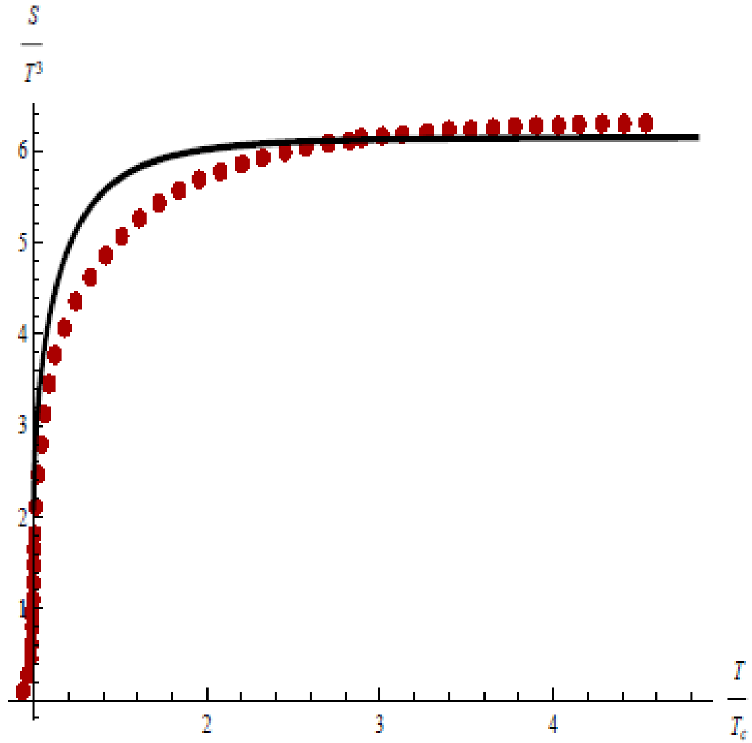
$$\left(z^2 f''(z) - 4f(z)\left(3z^2 A_s''(z) - 2z^2\phi''(z) + z^2\phi'(z)^2 + 3\right)\right).$$

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

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

$$s = \frac{A_{area}}{4G_5V_3} = \frac{L^3}{4G_5}\left(\frac{e^{A_s-\frac{2}{3}\phi}}{z}\right)^3.$$



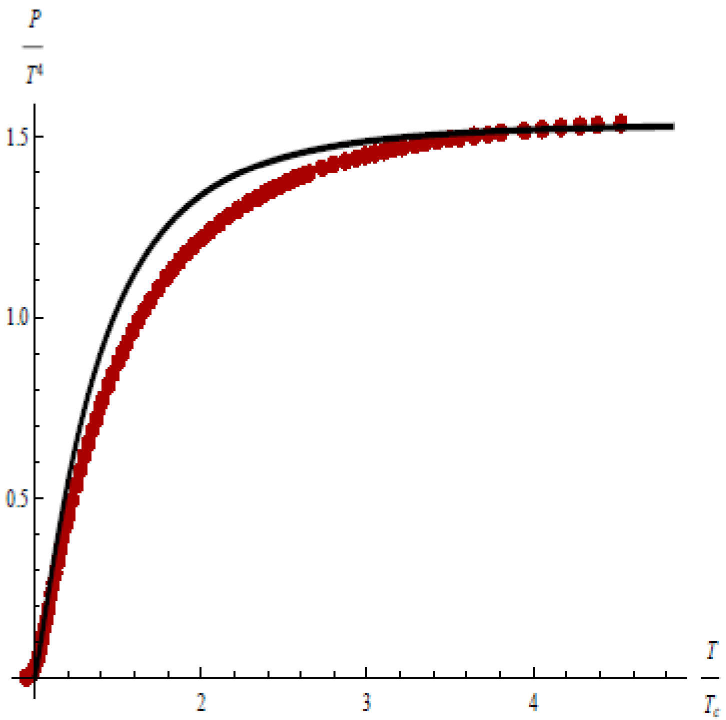


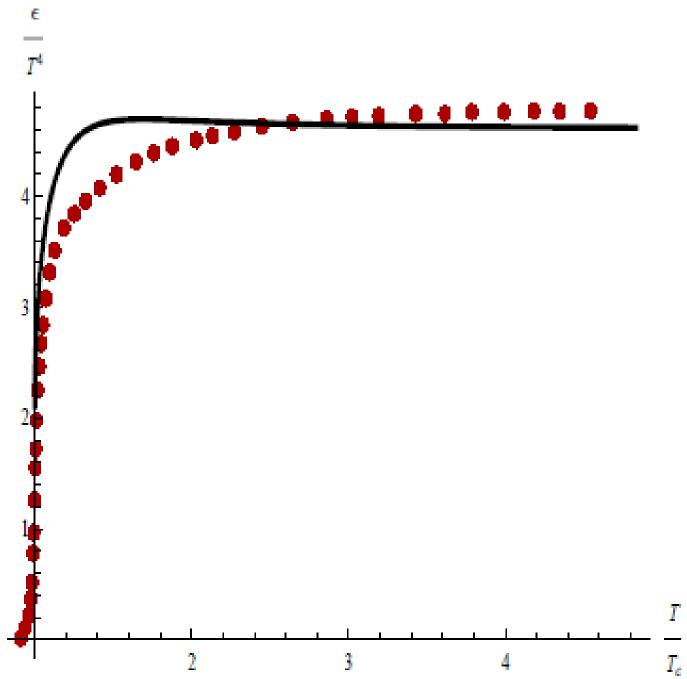
$T_c = 201\text{MeV}$

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

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

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

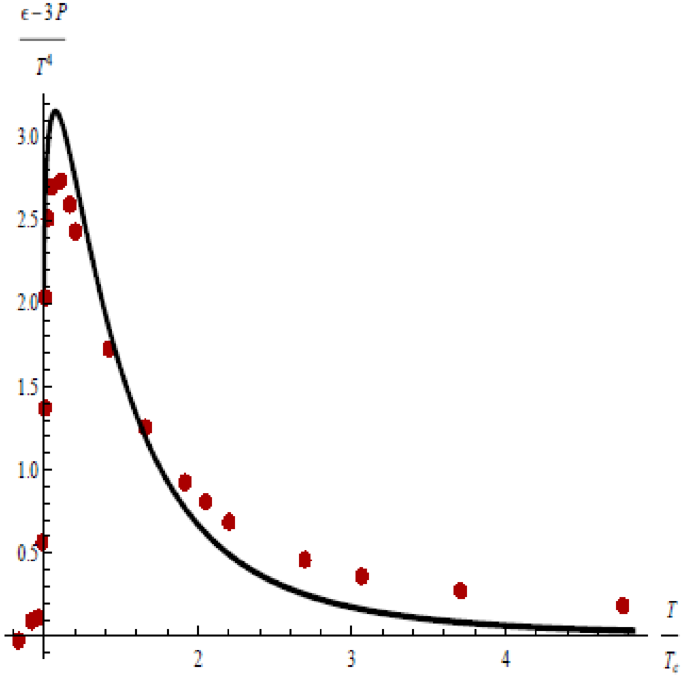


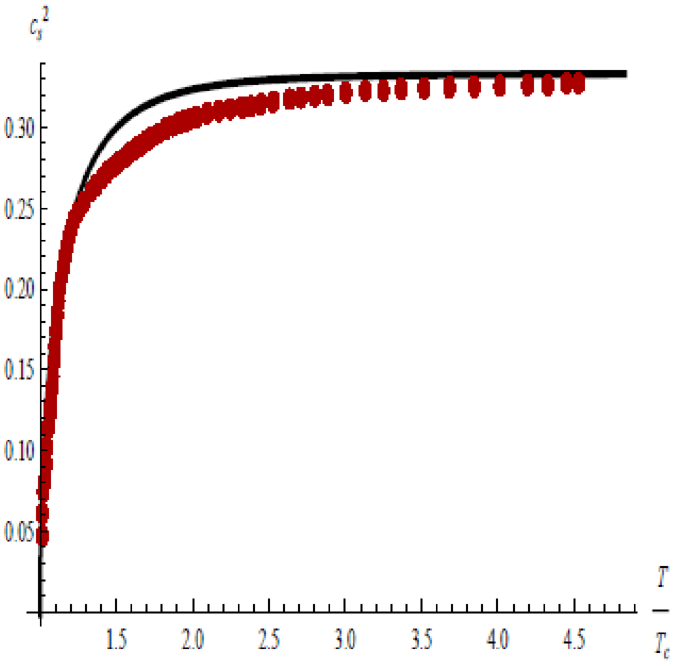


D.N. Li, S. He, M.H., Q. S. Yan, arXiv:1103.5389, JHEP2011

Trace anomaly

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

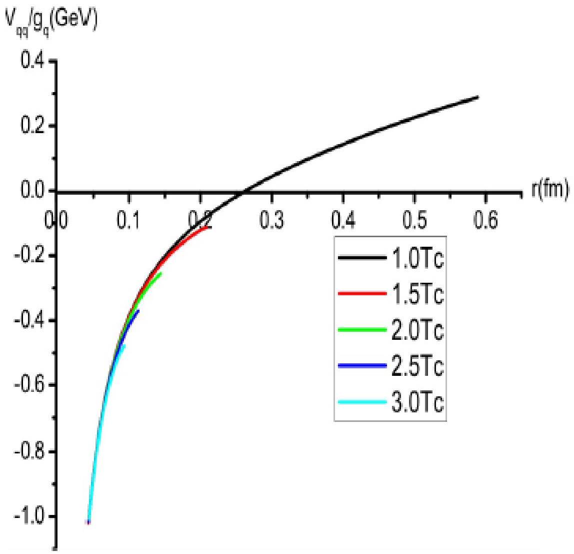


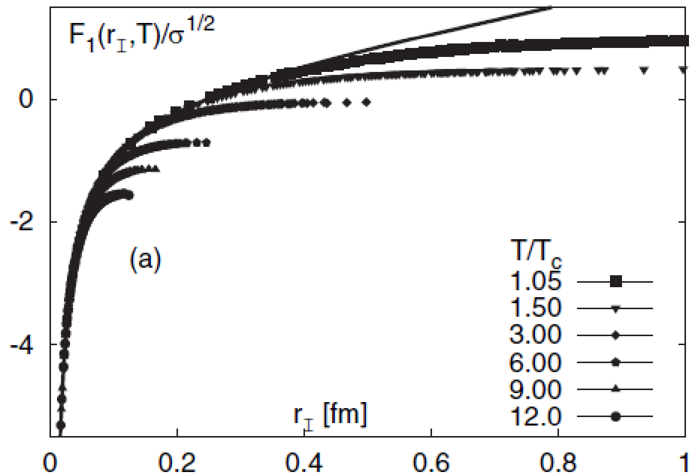


D.N. Li, S. He, M.H., Q. S. Yan, arXiv:1103.5389, JHEP2011

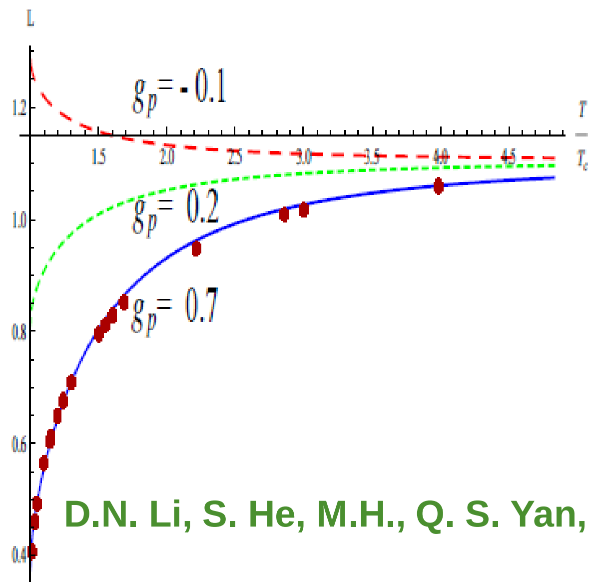
Electric screening

Heavy quark potential



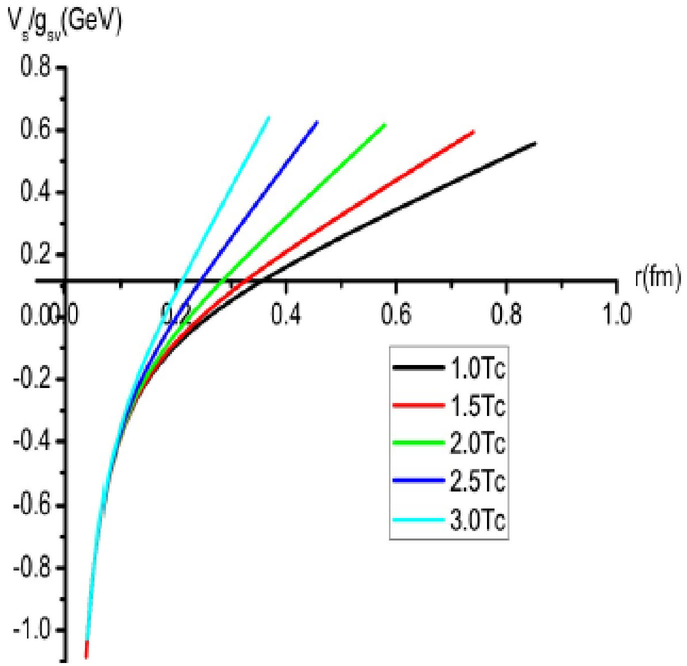


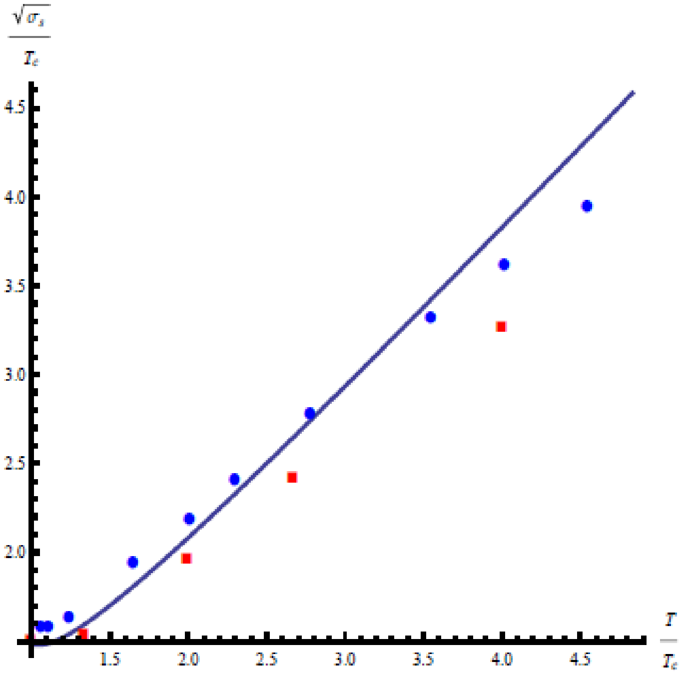
Polyakov loop: color electric deconfinement



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

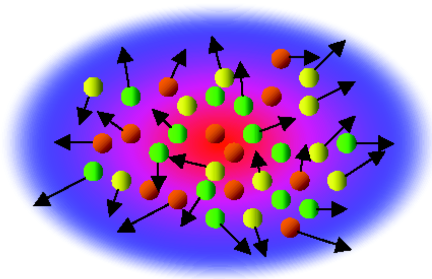
D.N. Li, S. He, M.H., Q. S. Yan, arXiv:1103.5389, JHEP2011

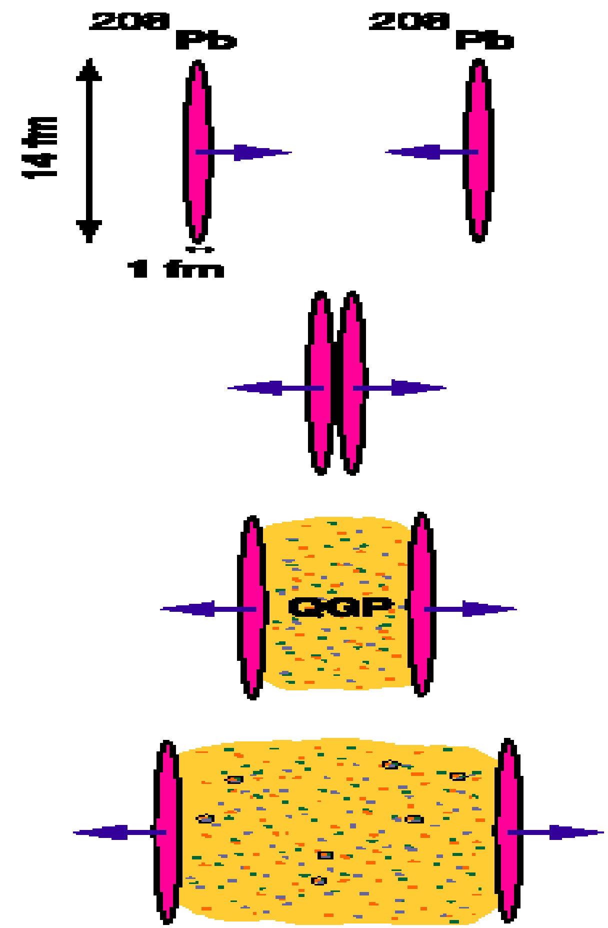
Transport properties

shear/bulk viscosity,
Jet quenching parameter

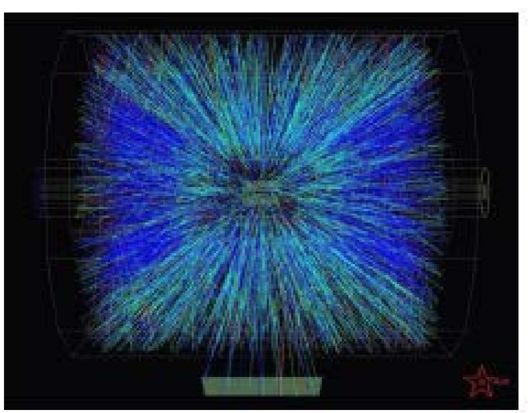
Discovery of “Perfect fluid” at RHIC

Relativistic Heavy Ion Collision





Hydrodynamics



A little bit Hydrodynamics

$$T^{\mu\nu}_{ideal} = (\epsilon + p)u^\mu u^\nu - p g^{\mu\nu}$$

$$T^{\mu\nu}_{NS} = T^{\mu\nu}_{ideal} + \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}\partial^\alpha u_\alpha) + \zeta\Delta^{\mu\nu}\partial^\alpha u_\alpha$$

η, ζ **shear and bulk viscosities**

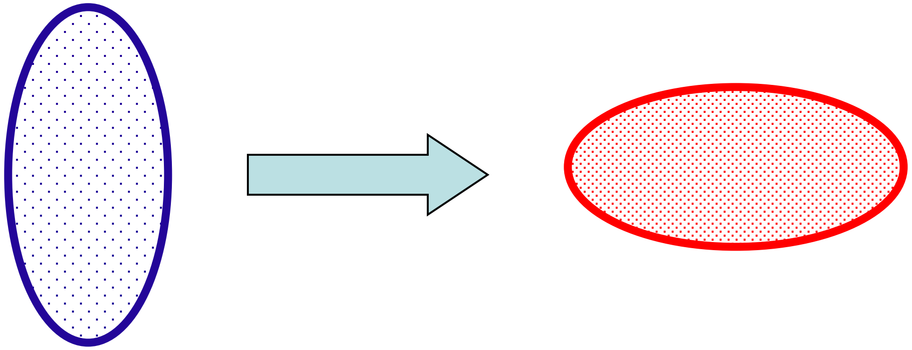
weak coupling gas: η *large*, $\xi \simeq 0$

pQCD calculations:
$\eta/s \simeq 0.8$ for $\alpha_s = 0.3$, →
$\xi/s = 0.02\alpha_s^2$ for $0.06 < \alpha_s < 0.3$

P. Arnold, G. D. Moore and L. G. Yaffe, JHEP **0305**, 051 (2003).

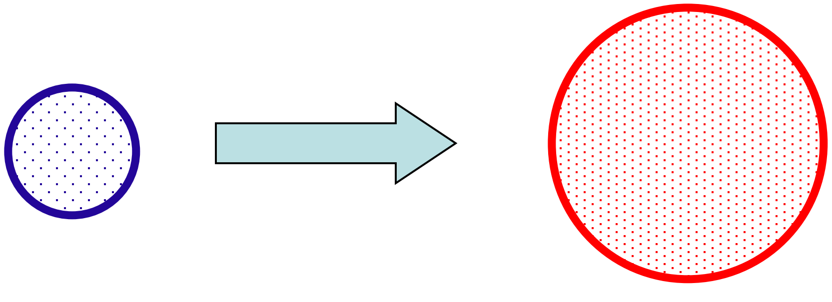
P. Arnold, C. Dogan and G. D. Moore, Phys. Rev. D **74**, 085021 (2006).

Shear viscosity: how much entropy is produced by transformation of shape at constant volume



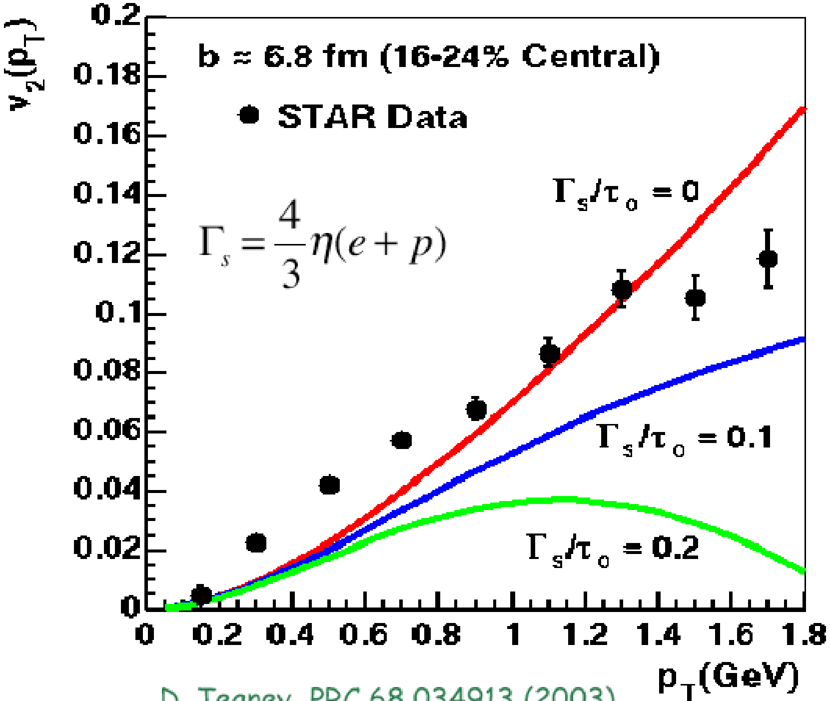
Generated by translations

Bulk viscosity: how much entropy is produced by transformation of volume at constant shape

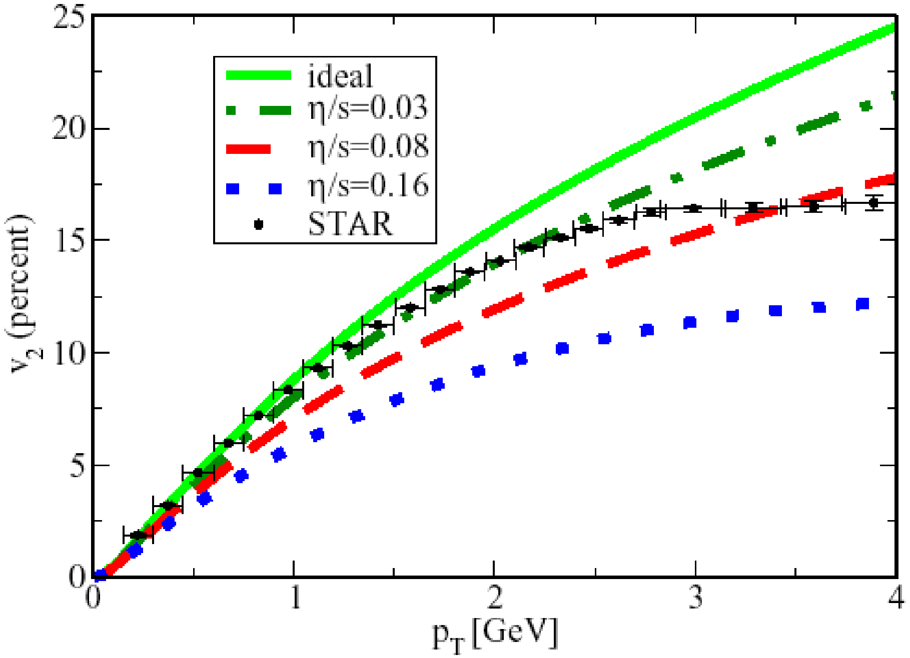


Generated by dilatations

Before 2003, people believed that de-confined QCD matter would be weakly coupled gas. Therefore, bulk viscosity is neglected, only consider shear viscosity corrections to the ideal hydro.



D. Teaney, PRC 68 034913 (2003)



P. Romatschke, U. Romatschke, nucl-th/0706.1522

Increase shear viscosity reduces elliptic flow!

Discovery of sQGP at RHIC

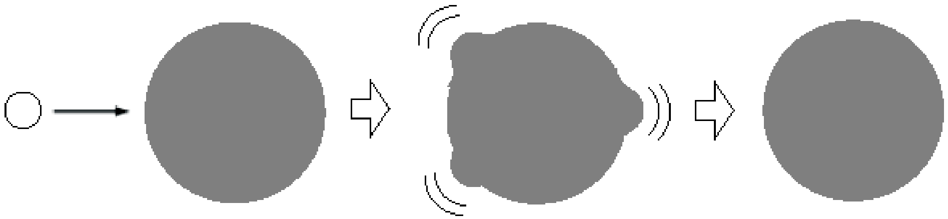
Low shear viscosity

$$\eta/s \approx 0.1...0.2$$

AIP Bulletin, April 20 2005:

Now, for the first time since starting nuclear collisions at RHIC in the year 2000 and with plenty of data in hand, all four detector groups operating at the lab [BNL] . . . believe that the fireball is a liquid of strongly interacting quarks and gluons rather than a gas of weakly interacting quarks and gluons.

Shear viscosity from AdS/CFT



shear viscosity ⇔ absorption cross section of graviton

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

entropy ⇔ horizon area

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

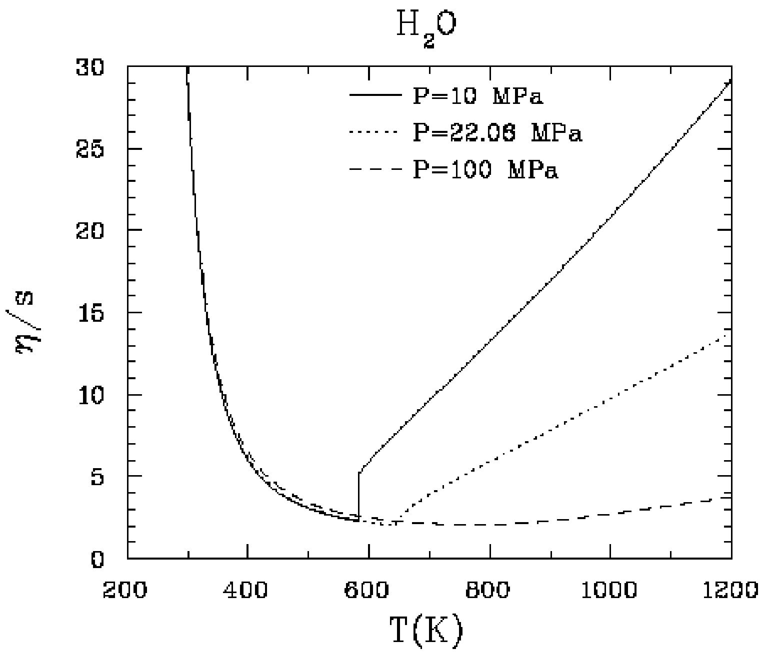
$$\frac{\eta}{s} = \frac{1}{4\pi}$$

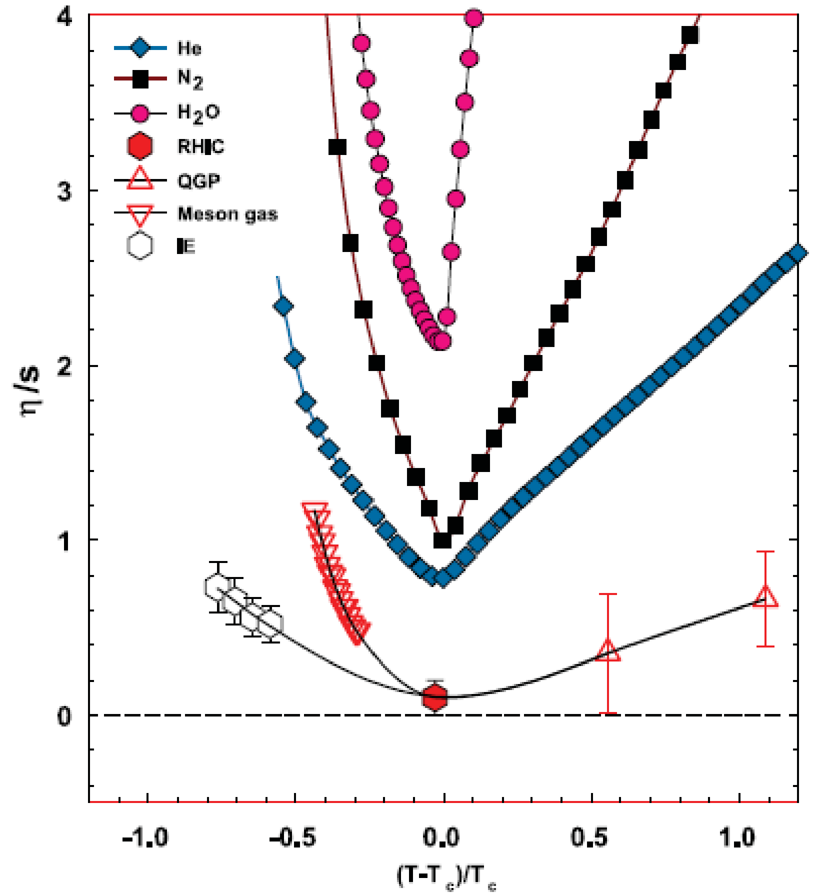
Minimum bound?

Kovtun - Son - Starinets (2004)

Shear viscosity over entropy density:

minimum near phase transition

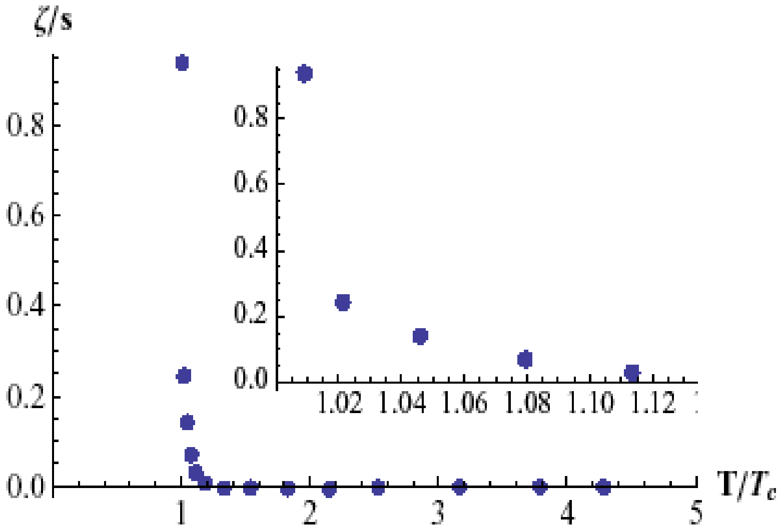




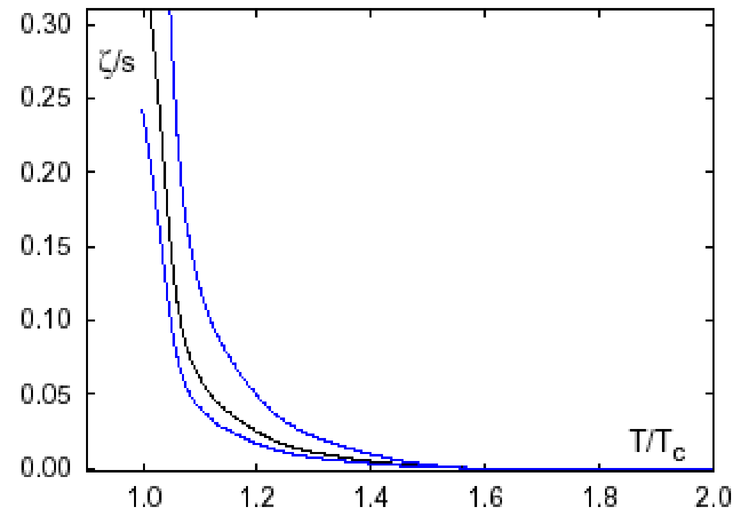
Csernai et.al. Phys.Rev.Lett.97:152303,2006

Lacey et al., PRL 98:092301,2007

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



Pure gluodynamics



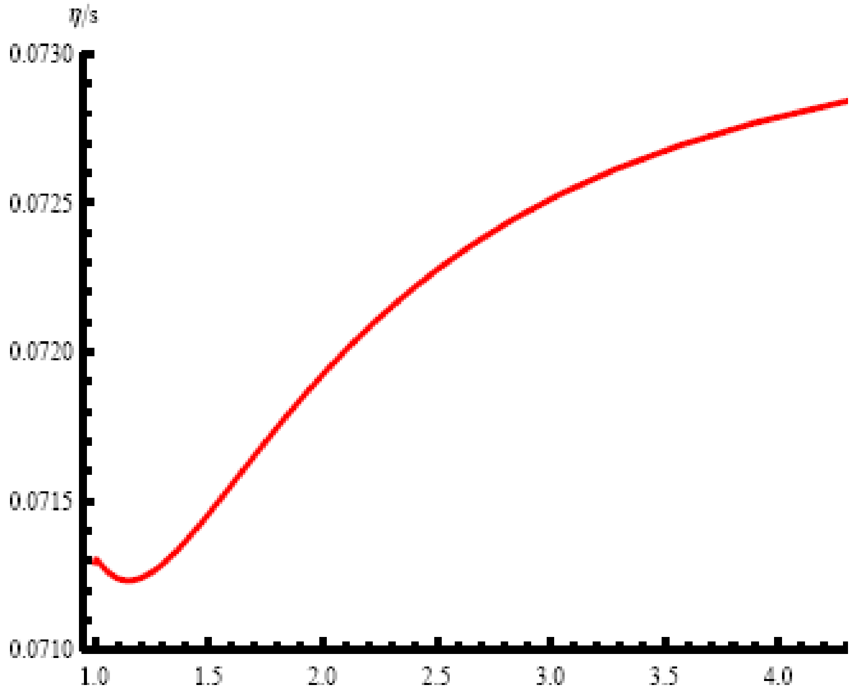
2-flavor case

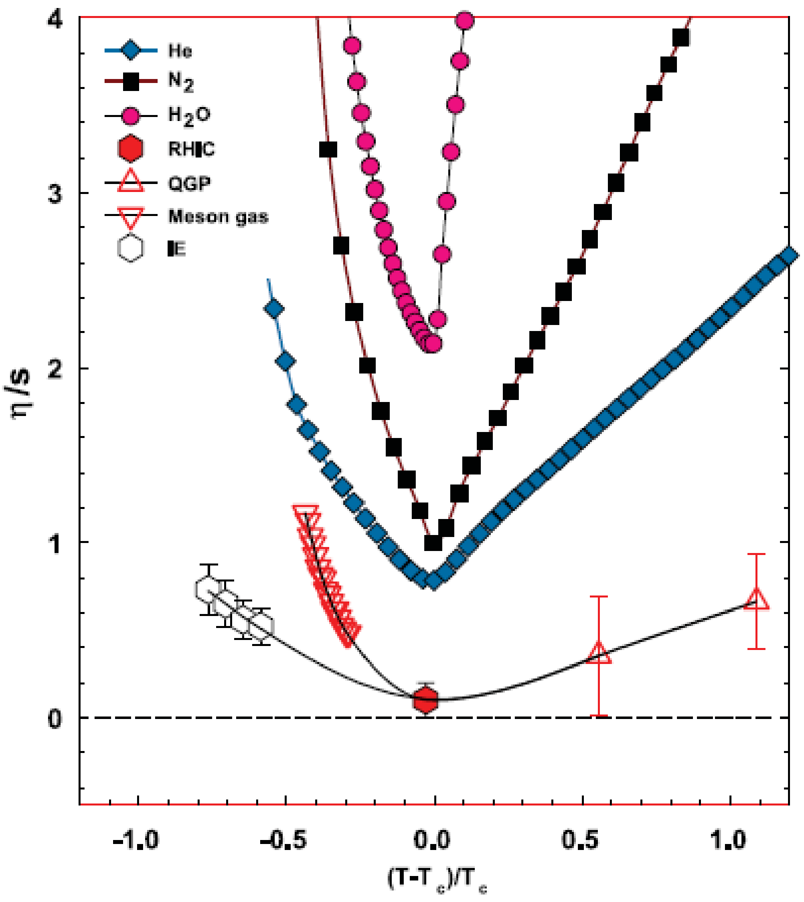
$$\zeta = \frac{1}{9\,\omega_0}\left\{T^5\frac{\partial}{\partial T}\frac{(\epsilon_T - 3p_T)}{T^4} + 16|\epsilon_v|\right\}$$

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

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

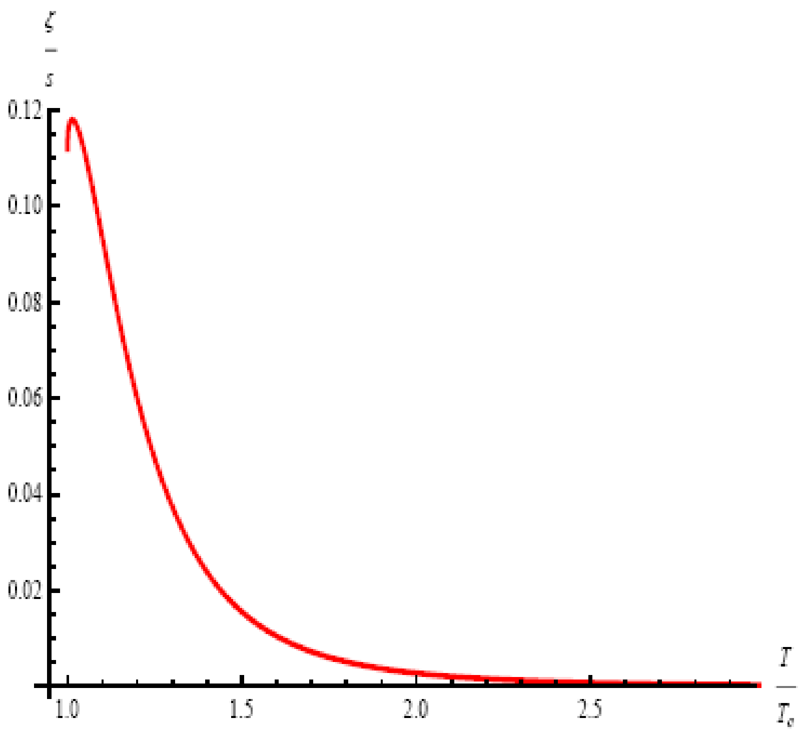


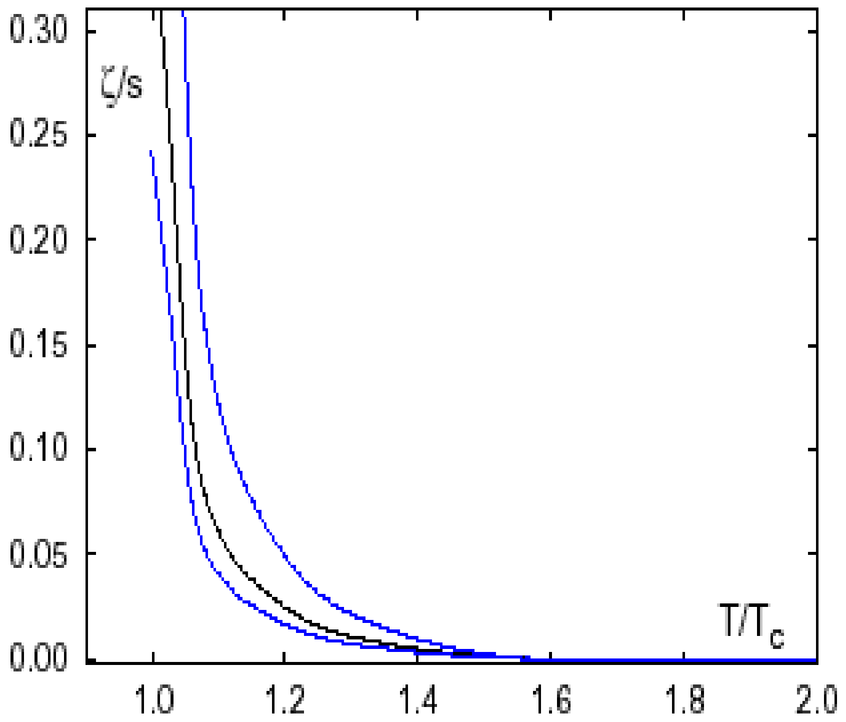


Danning Li, Song He, M.H. JHEP2015

Lacey et al., PRL 98:092301,2007

Bulk viscosity from dynamical hQCD

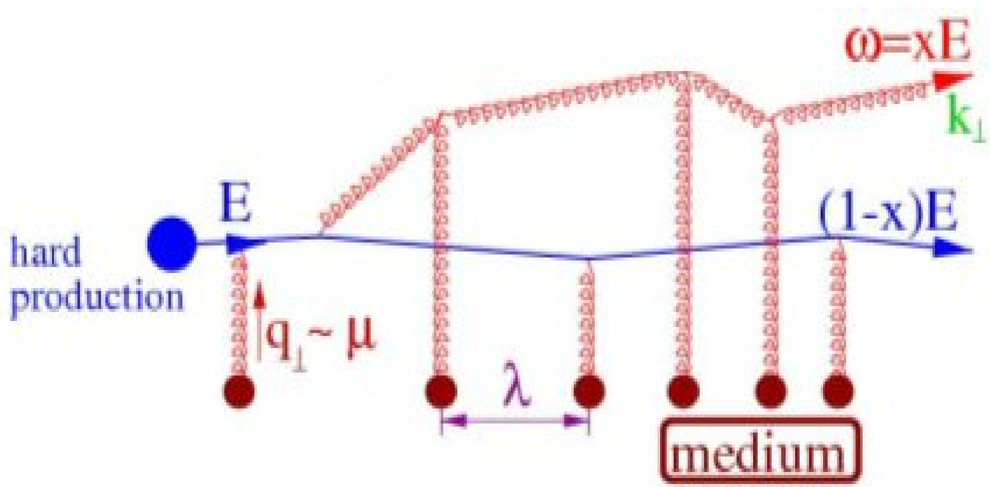


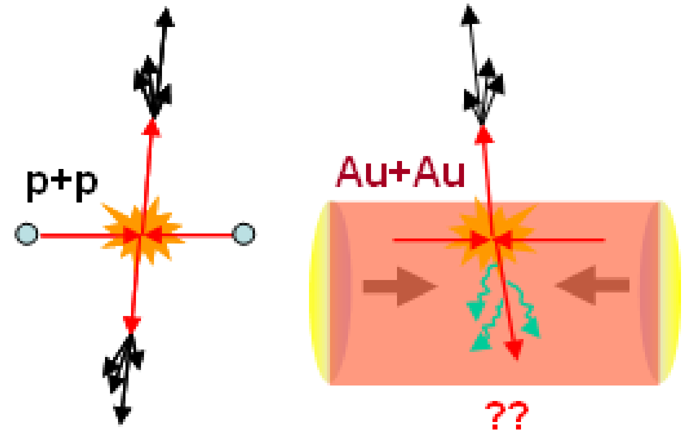


Danning Li, Song He, M.H. JHEP2015

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):

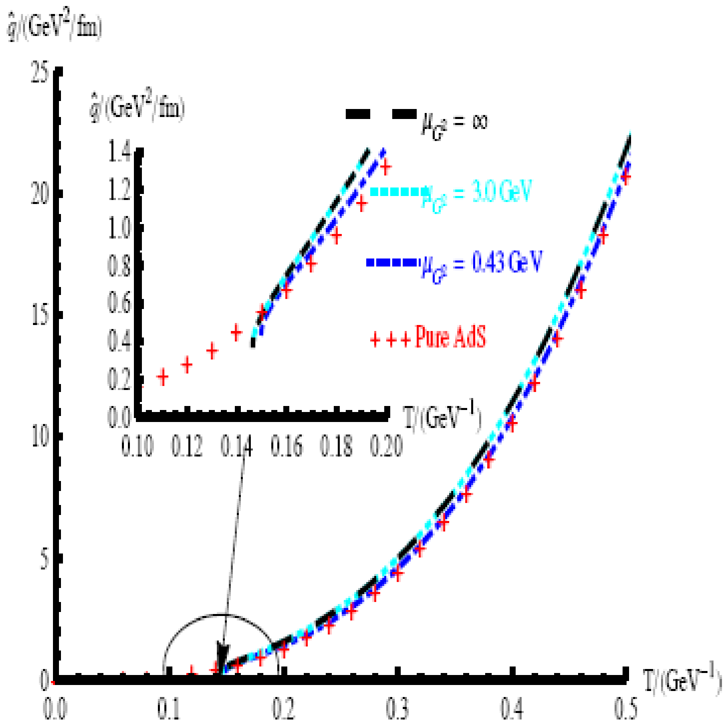
$\hat{q}$: reflects the ability of the medium to "quench" jets.

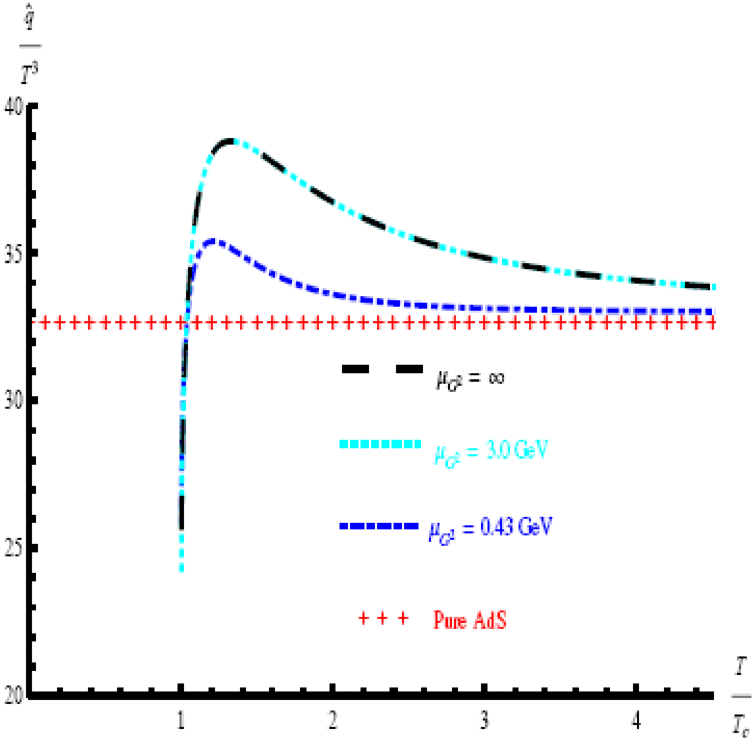
$$\hat{q} = \frac{\langle k_T^2 \rangle}{L} \approx \frac{\mu^2}{\lambda}$$

μ : Debye mass λ : mean free path

Jet quenching from dynamical hQCD

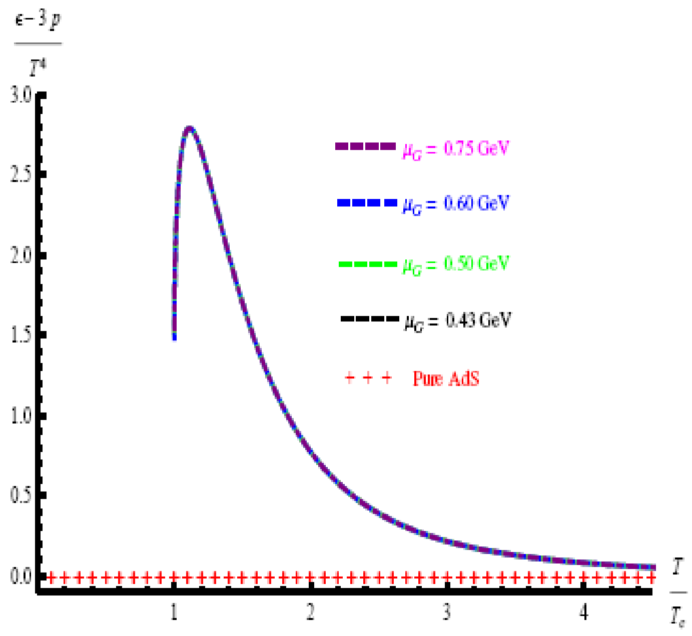
Danning Li, Jinfeng Liao, M.H. PRD2014

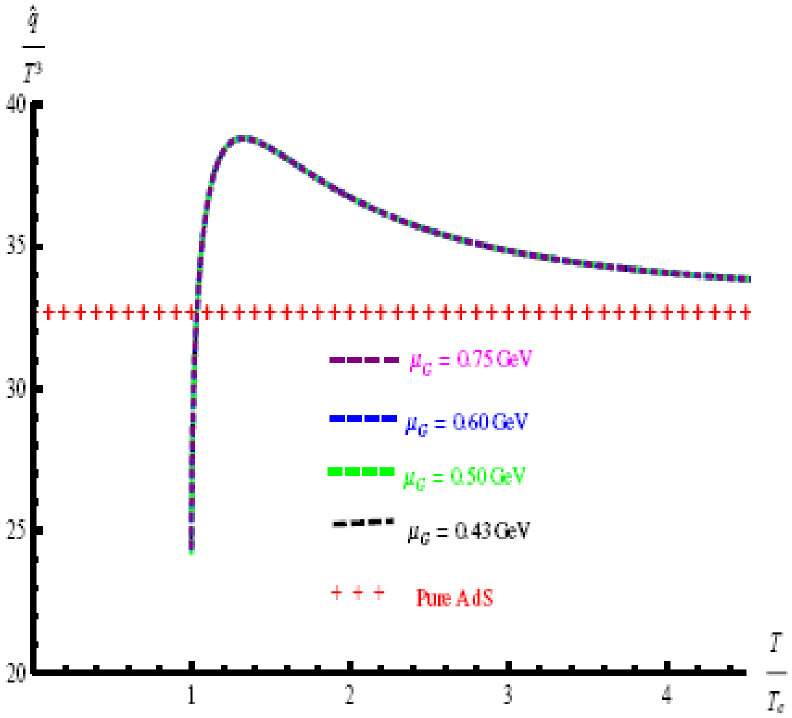




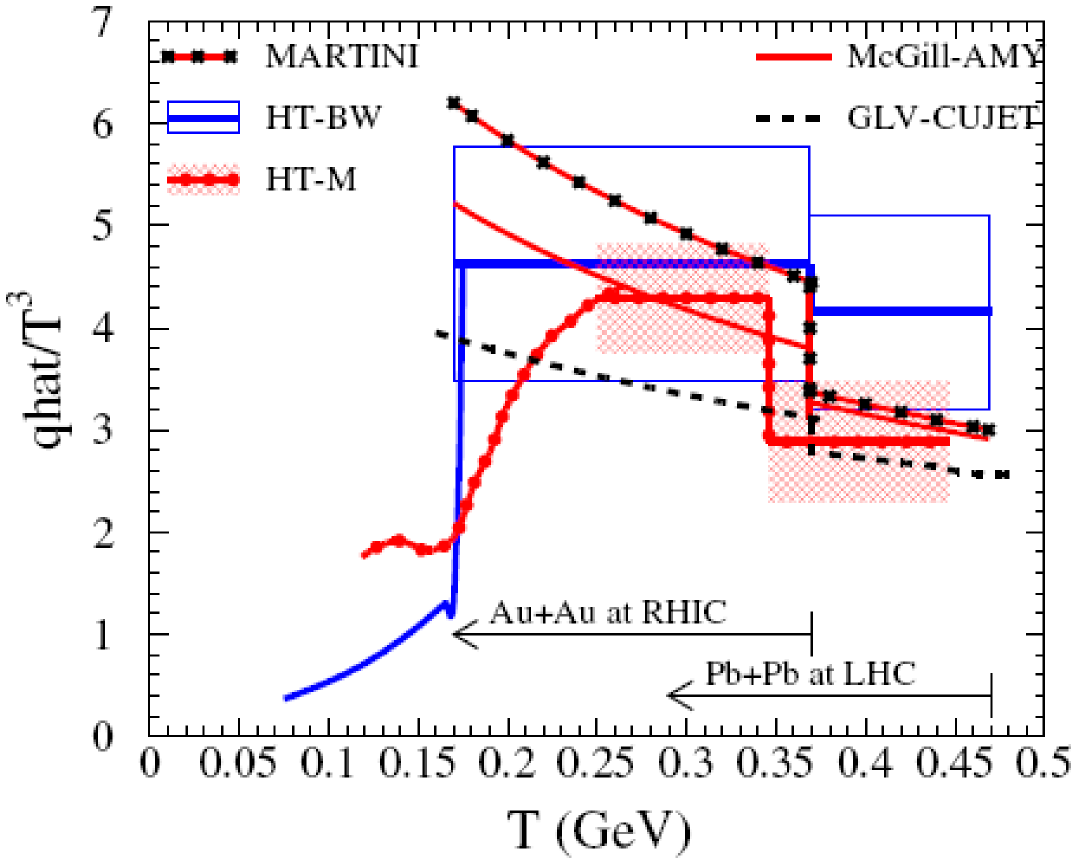
Jet quenching characterizing phase transition!

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

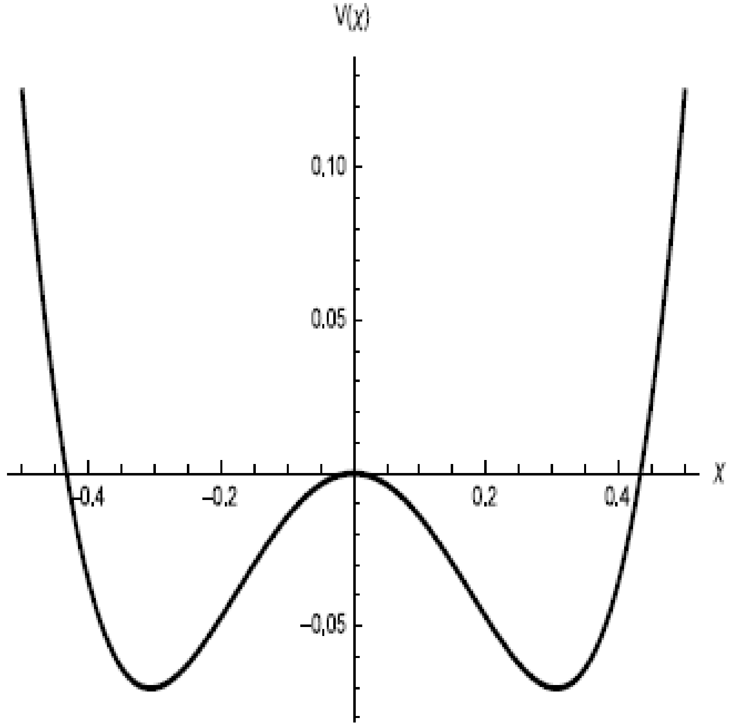
$$V(\chi) \equiv Tr(V_X(|X|)) = -\frac{3}{2}\chi^2 + v_3\chi^3 + v_4\chi^4.$$

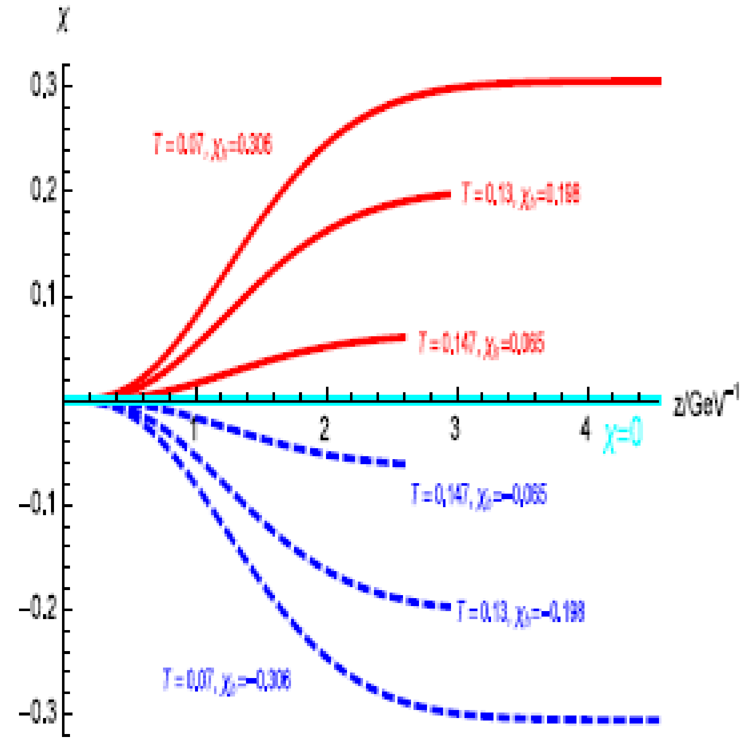
Only for three-flavor scalar

Profile of the dilaton field

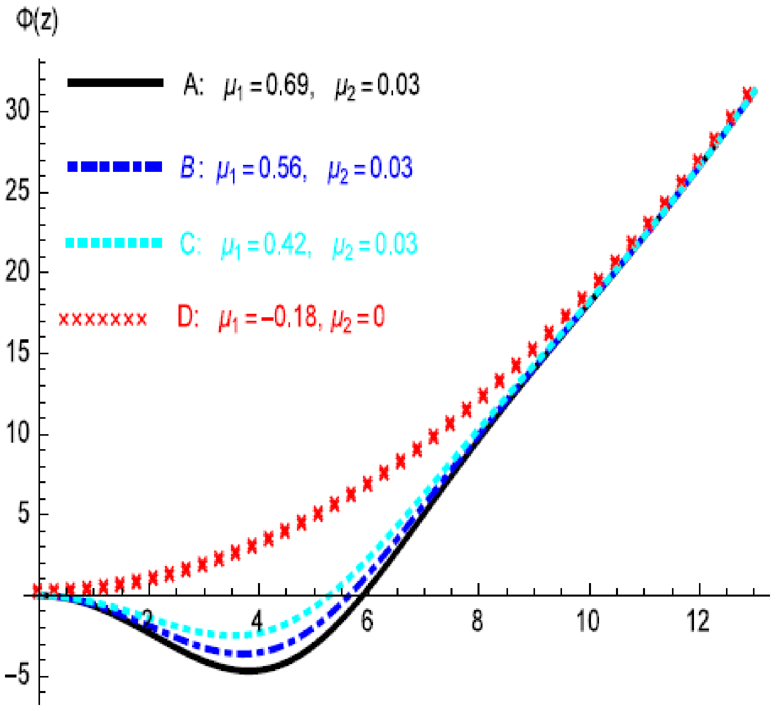
$$\Phi(z) = -\mu_1 z^2 + (\mu_1 + \mu_0)z^2\tanh(\mu_2 z^2),$$

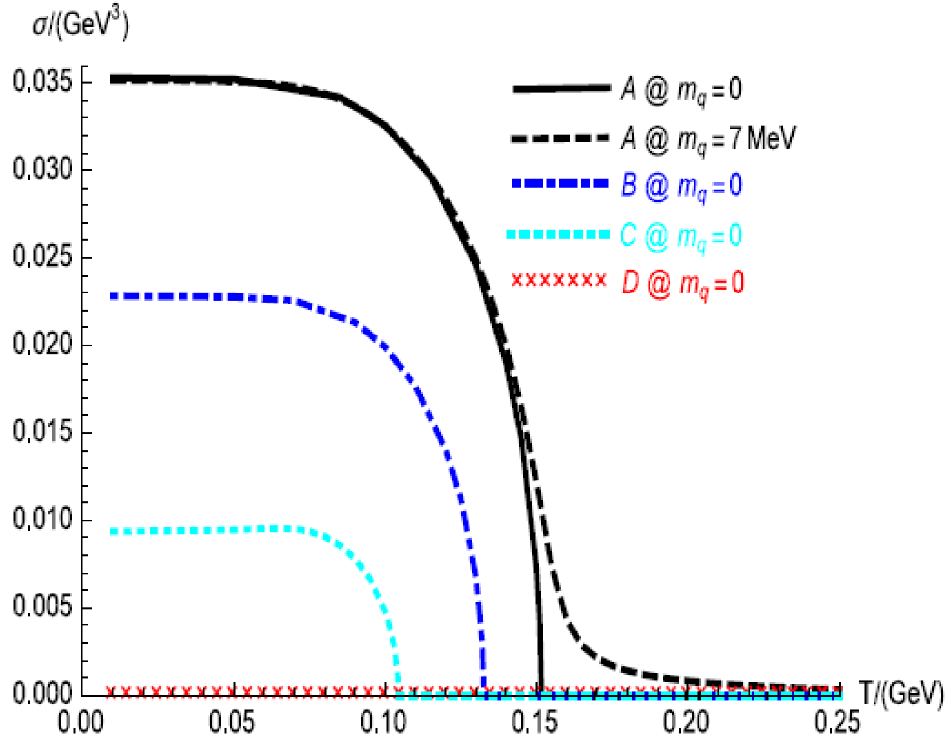
Profile of the scalar potential determines the possible solution of the chiral condensate





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

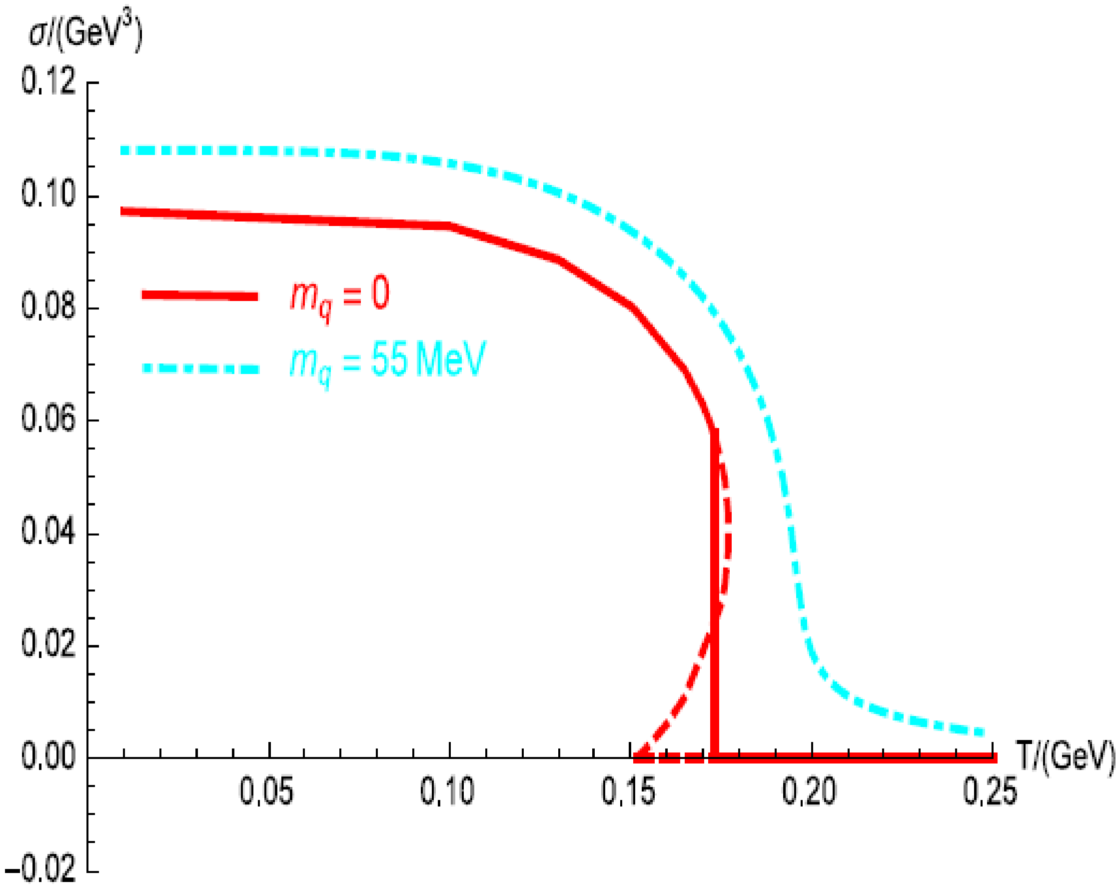




Two-flavor case:

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

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

For the future …

Heavy flavor Hadron spectra?
Exotic states?
PDF?

Thanks for your attention!