Study energy loss in an anisotropic sQGP with holographic QCD

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Outline

I. Heavy ion Collisions and Jet quenching

II. A HQCD model with anisotropy

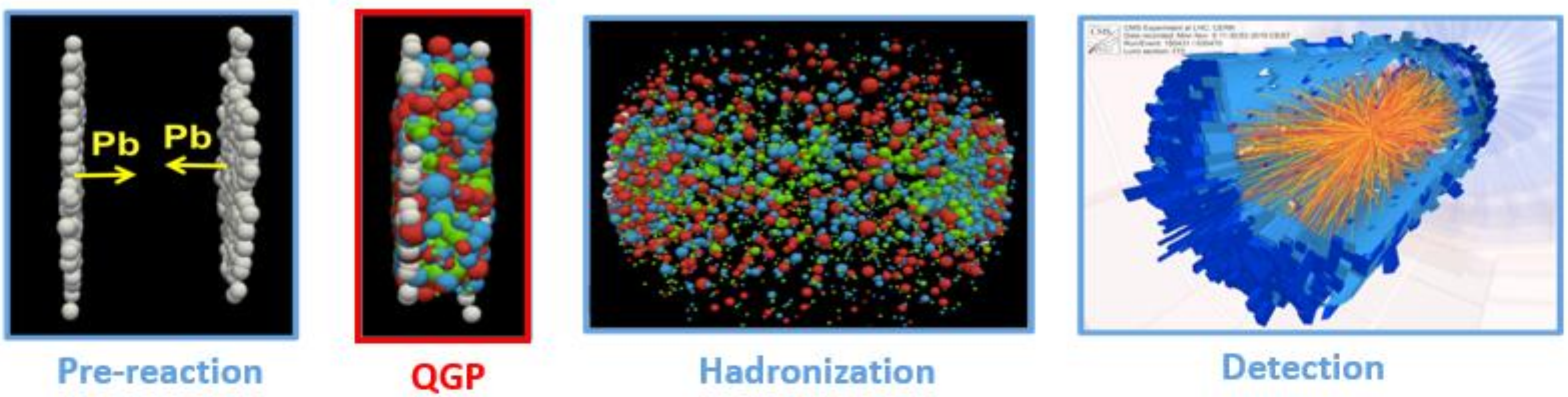
III. Jet quenching parameter

IV. Heavy quark energy loss (trailing string)

V. Summary

HICs and anisotropic QGP

The Heavy Ion Collision provides a novel window to study the strong coupled QCD.



should possess an anisotropic phase for $0.1 \lesssim \tau \lesssim 0.3-2\ fm/c$.

- **The pressure of the QGP in transverse direction may be lager than the pressure along the beam direction .**

$\frac{P_L}{P_T} \sim (0.35, 0.5).$

Nucl.Phys.A 926 92-101

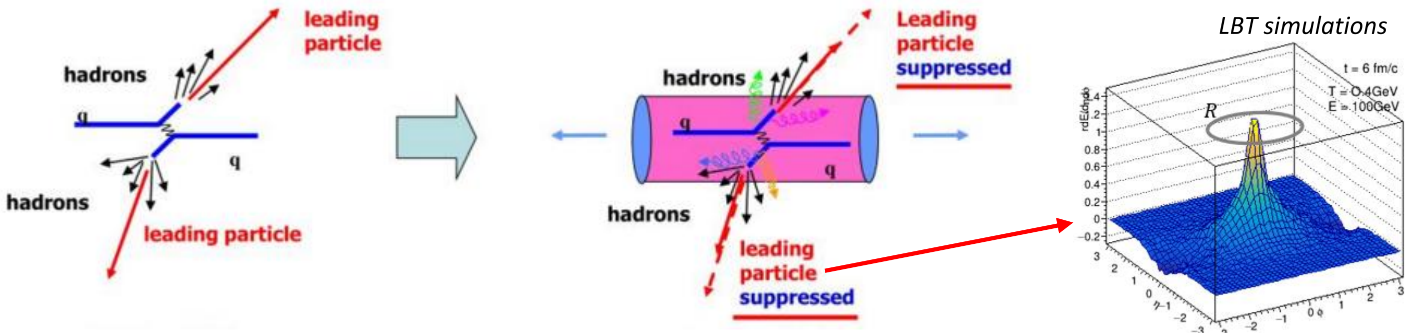
- **The anisotropic holographic QCD model can reproduce the energy dependence of the total particle multiplicity in HICs.**

$\mathcal{M} \sim s^{0.155}$

JHEP 04 (2015) 011

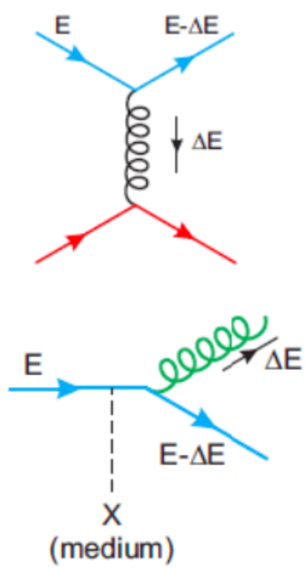
- **Other sources relate to $\mathfrak{B}$, glasma, spatial (v_2) ⋯**

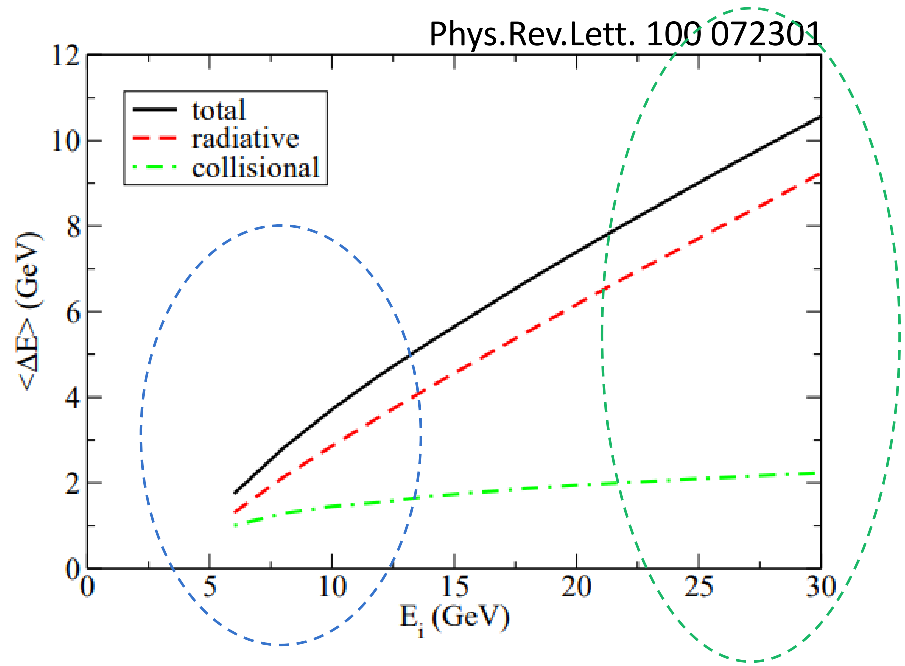
HICs and high p_T jet energy loss



Studying energy loss offers a method to study the properties of QGP.

Energy loss in 2 channels

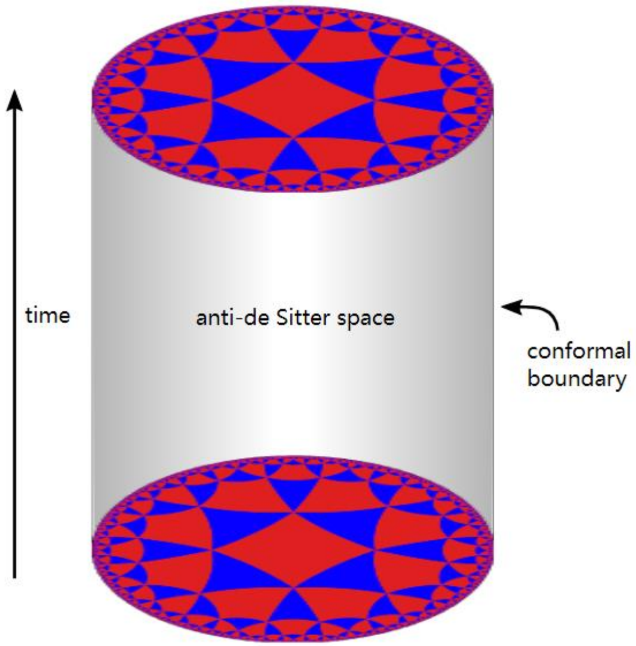




- **The high p_T → inelastic process: gluon bremsstrahlung.**
- **The low p_T → elastic scattering: collision with thermal partons.**

II. AdS/CFT

- **Holographic principle** 't Hooft and Susskind in 1994
- *$\mathcal{N} = 4$ SYM on the boundary $\Longleftrightarrow$ Type IIB string theory in the bulk* Maldacena in1997
- $\left\langle e^{\int d^4x \phi_0(\vec{x}) O(\vec{x})} \right\rangle_{\text{CFT}} = Z_{string}[\phi(\vec{x}, z)|_{z=0} = \phi_0(\vec{x})]$
Gubser, Klebanov, Polyakov in 1998; Witten in 1998



Taken from www.wikipedia.org

Limits $N_c \to \infty$ and Large λ

$$Z_{string}[\phi(\mathrm{x}, 0)] = e^{-I_{sugra}[\phi_0(x)]}|_{\phi(\mathrm{x},0)=\phi_0(x)},$$

$$I_{sugra}[\phi] = \text{classical supergravity action.}$$

Due to the presence of a large number of D-branes, spacetime is curved into an anti-de Sitter (AdS) spacetime with maximal symmetry and negative constant curvature.

The weak form AdS/CFT is a strong/weak coupling duality

String coupling g_s, AdS radius R, String length l_s.
Yang-Mills coupling g_{YM}, Rank of the gauge group N_c.

$$g_s = g_{YM}^2$$

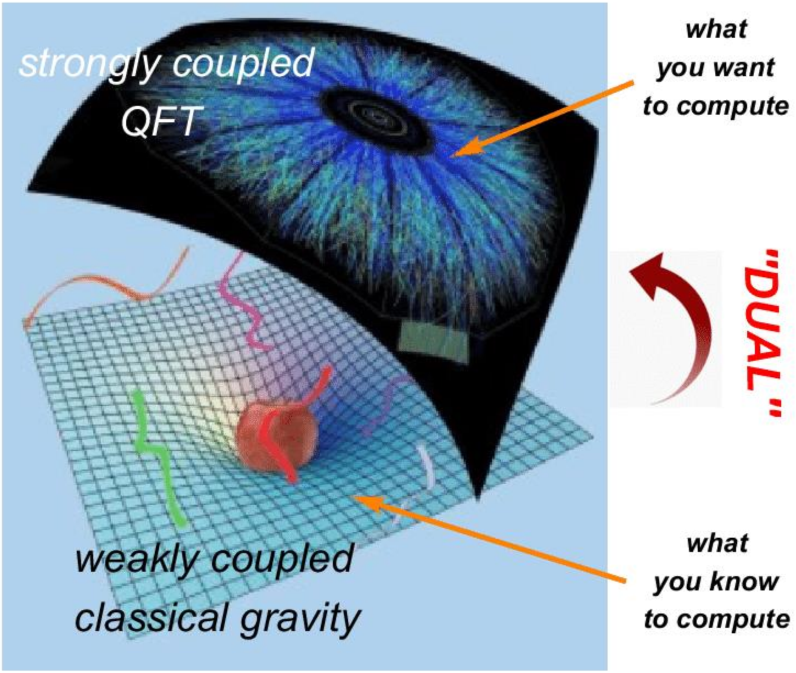
$$\left(\frac{R}{l_s}\right)^4 = \lambda \; (\equiv g_{YM}^2 N_c)$$

weak form ↓ $N_c \to \infty$, λ $large$

$g_s \to 0$ and $R \gg l_s$ — $\lambda \gg 1$

Classical SUGRA ⇋ **Strongly coupled theory**

This provides a powerful tool for studying strongly coupled gauge theories with gravity.



Applied Holography, Springer Briefs in Physics

Finding a gravity dual to QCD is an important aim of the correspondence.

Gravity? ⇋ **QCD**

Potential reconstruction and gravity-dilaton system

Break conformal symmetry:

The presence of dilaton field ϕ breaks conformal invariance in a way consistent with known QCD thermodynamics.

- **The minimal noncritical 5D effective gravity action**

$$S = \frac{1}{16\pi G_5}\int d^5x\sqrt{-g}\left[R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\right]$$

Warped factor: a single factor can capture the main features of non-perturbative QCD physics.

Blacken factor for finite T

The soft-wall AdS/QCD for hadron physics.

$$ds^2 = \frac{Le^{2\mathcal{A}(z)}}{z^2}\left[-f(z)dt^2 + \frac{dz^2}{f(z)} + d\vec{x}^2\right]$$

Deformed Metric | Dilaton field | Dilaton potential

should be solved in the equation of motion consistently

- **The potential reconstruction method (analytically)**

Song He, Mei Huang, Danning Li, Qi-Shu Yan, Rong-Gen Cai

$$\mathcal{A}(z) = cz^2$$

for example

One can find the solution of motion only depends on a single scale factor $\mathcal{A}(z)$.
This scale function will be further chosen by taking inputs from real QCD and Lattices results.

A HQCD model with anisotropy

Einstein-dilaton-two-Maxwell-scalar action

The magnetic part of Maxwell tensor introduced to provide anisotropy.

$$S = \frac{1}{16\pi G_5}\int d^5x\sqrt{-g}\left[R - \frac{f_1(\phi)}{4}F_{(1)}^2 - \frac{f_2(\phi)}{4}F_{(2)}^2 - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\Phi)\right]$$

The charged part of Maxwell tensor introduced to provide chemical potential.

Anisotropic metric ansatz (Lifshitz-type background)

$$ds^2 = \frac{L^2}{z^2}e^{2\mathcal{A}(z)}\left[-g(z)dt^2 + dx^2 + \left(\frac{z}{L}\right)^{2-\frac{2}{A}}(dy_1^2 + dy_2^2) + \frac{dz^2}{g(z)}\right]$$

The boundary is at $r = 0$; A=1 reduce to AdS-BH case.

- The arbitrary dynamical parameter $A \in (1,1.05)$, $A=1$ it reproduces previous known solutions in isotropic case .
- A well tested $\mathcal{A}(z) = -a\ln(\mathrm{b}z^2 + 1)$, can capture many properties of QCD near the CP.
- a = 4.046, b = 0.01613 following JHEP 04, 093 (2013) in isotropic case. These values are due to the mass spectrum of ρ meson with its excitations and also due to the lattice results for the phase transition temperature $T_c = 0.1578$ GeV.
- Denote the x as the direction of anisotropy, for the rotation symmetry in y_1y_2 plane.

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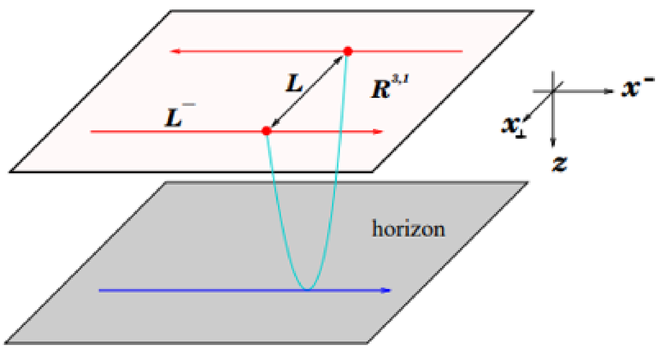
III. $\hat{q}$ in holographic QCD

$$\hat{q} \equiv \frac{\langle k_\perp^2 \rangle}{L} = \frac{1}{L}\int \frac{d^2 k_\perp}{(2\pi)^2} k_\perp^2 P(k_\perp).$$

- Mean transvers momentum picked up per unit distance, is crucial to calculate radiation energy loss.



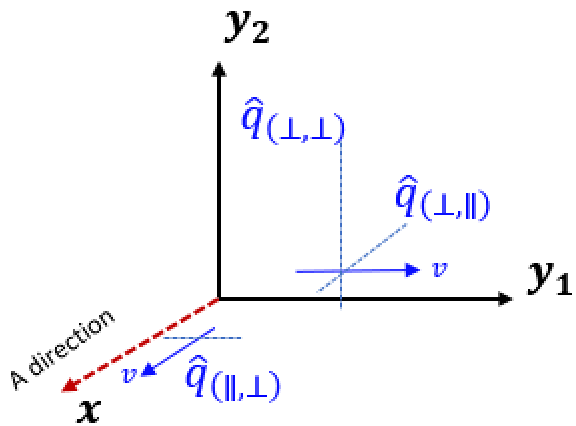
- q̂ is related to the light-like Wilson loop, and the expectation value of the Wilson loop is proportional to minimum area of the string world sheet.

$$\hat{q} \equiv \frac{-4\sqrt{2}}{L^- x_\perp^2} ln\langle W^A[C]\rangle = 8\sqrt{2}\frac{(S[C]-S_0)}{L^- x_\perp^2}$$

$$\hat{q}_{SYM} = \frac{\pi^{\frac{3}{2}}\Gamma\left(\frac{4}{3}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3.$$

Liu, Rajagopal and Weidemann Phys. Rev. Lett. 97, 182301

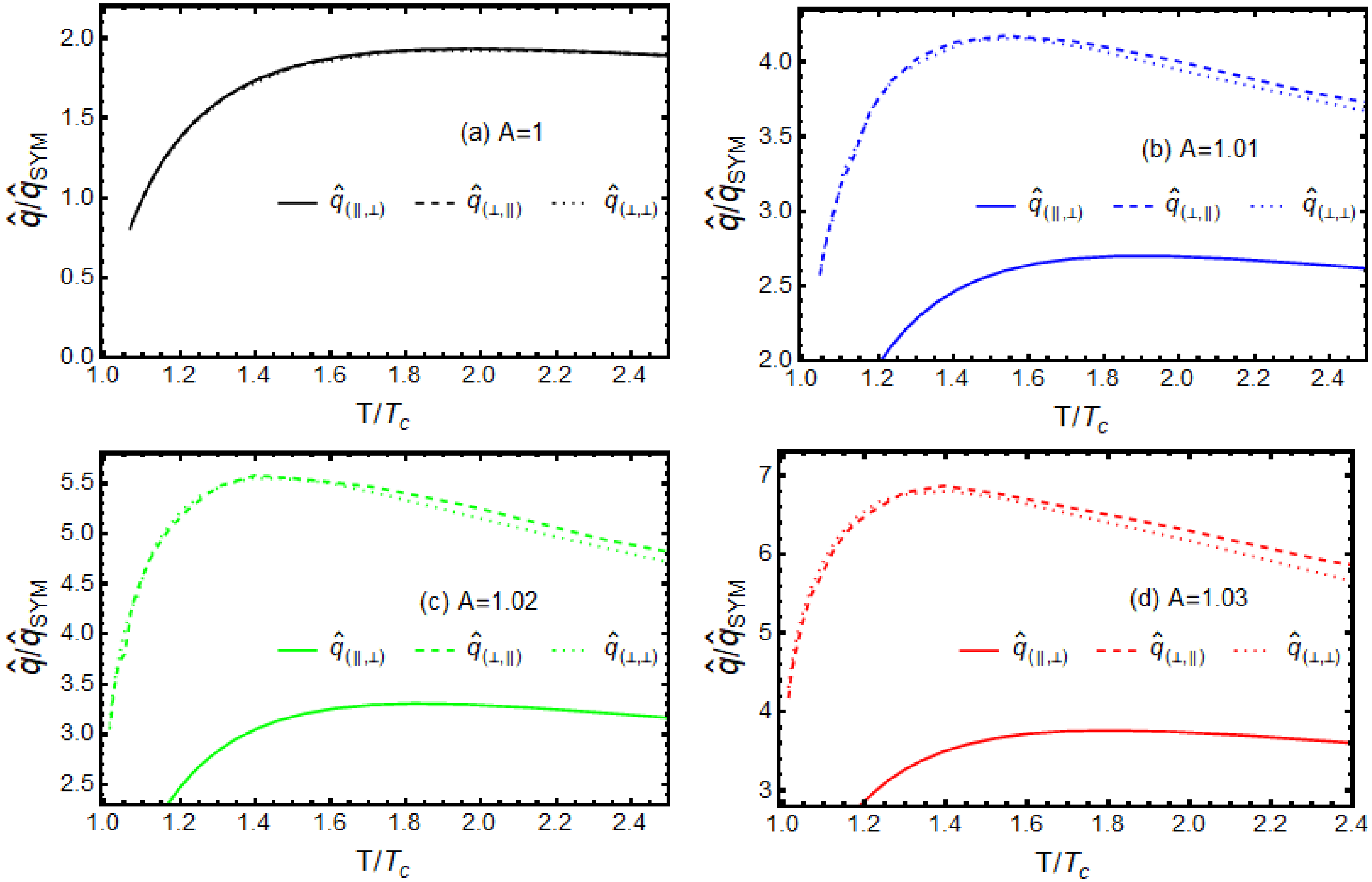
$$ds^2 = \frac{L^2 e^{2\mathcal{A}(z)}}{z^2}\left[-g(z)dt^2 + \frac{dz^2}{g(z)} + dx^2 + \left(\frac{z}{L}\right)^{2-\frac{2}{A}}(dy_1^2 + dy_2^2)\right]$$



Since the anisotropy of the geometry in spatial space, there should be three different jet quenching parameters.

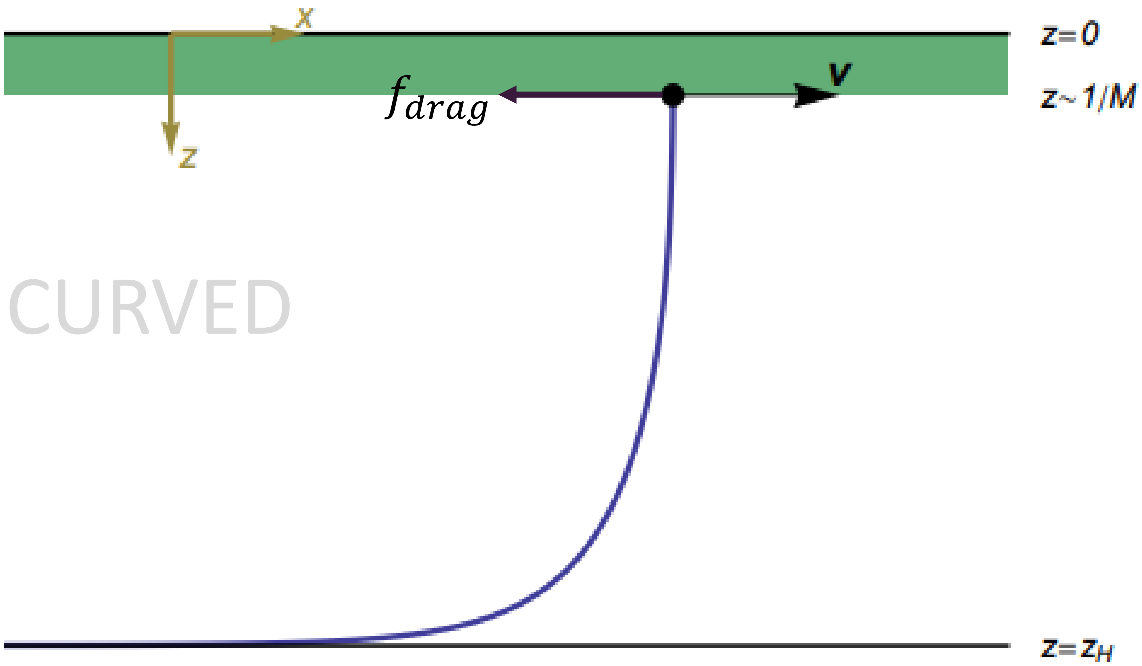
$$\hat{q}_{(\parallel,\perp)},\ \hat{q}_{(\perp,\parallel)},\ \hat{q}_{(\perp,\perp)}$$

Results-a： Jet quenching parameter



- The anisotropy increases $\hat{q}_{(\parallel,\perp)}, \hat{q}_{(\perp,\parallel)}, \hat{q}_{(\perp,\perp)}$.
- A small peak around critical temperature.
- $\hat{q}_{(\parallel,\perp)} < \left(\hat{q}_{(\perp,\parallel)} \sim \hat{q}_{(\perp,\perp)}\right)$

IV. The heavy quark energy loss

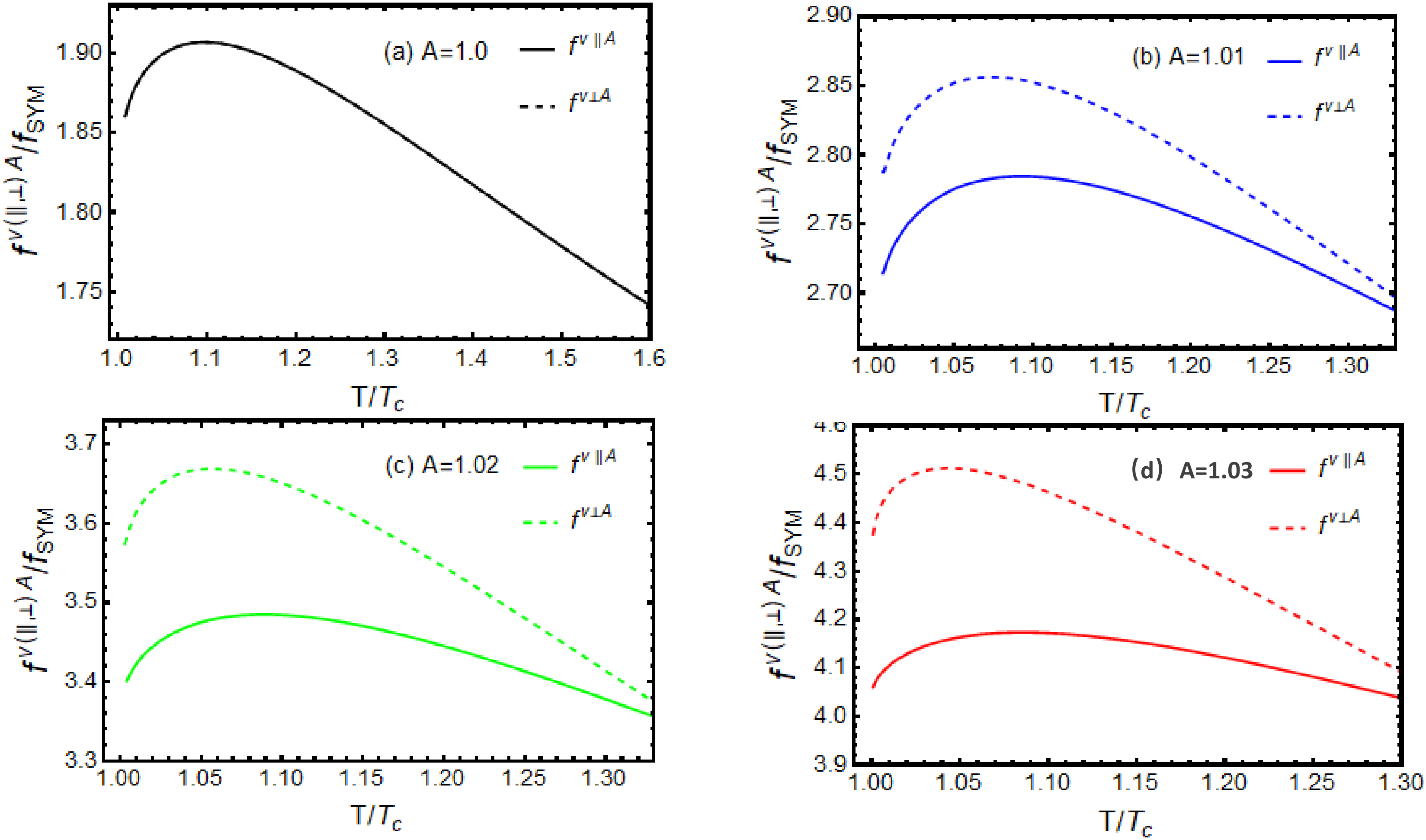


A heavy quark propagates in sQGP is assumed to be dual to the problem of the string drag between the D7 probe brane and D3 black branes that serves as a geometric model of the sQGP phase.

$$f_{SYM} = \frac{\pi T^2\sqrt{\lambda}}{2}\frac{v}{\sqrt{1-v^2}} = \frac{\pi m T^2\sqrt{\lambda}}{2}p$$

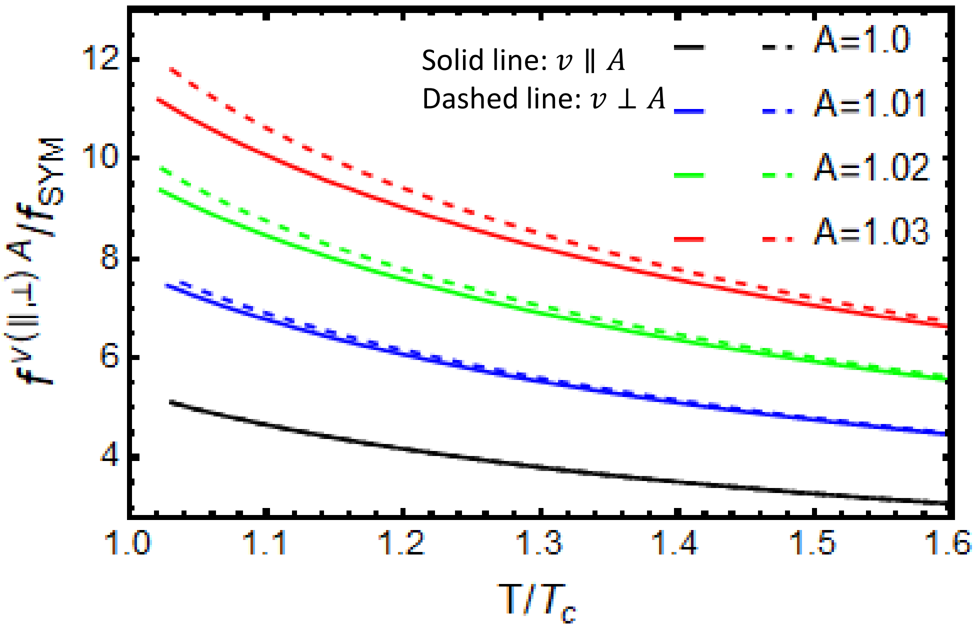
C. P. Herzog et al,JHEP 0607, 013 (2006)
S. S. Gubser, Phys. Rev. D 74, 126005 (2006)

Results-b： Drag force at v=0.96



- The anisotropy increases $f^{v\parallel A}$ and $f^{v\perp A}$.
- A small peak around critical temperature.
- $f^{v\parallel A} < f^{v\perp A}$.

Results-b： Drag force at v=0.6



- The anisotropy increases drag forces when moving both along and transverses to the anisotropy direction.
- Energy loss is stronger when moving transverse to anisotropic direction.
- The faster charm quarks are more sensitive to anisotropic background.

V. Summary

We study the energy loss of a quark moving in the sQGP under the influences of the anisotropy. The jet quenching parameters and heavy quark drag forces are calculated with the Einstein-Maxwell-dilaton(EMD) model, where the anisotropic background is specified by an arbitrary dynamical parameter A.

- The increasing anisotropy will increases the energy loss of partons (the drag forces and the jet quenching parameters).
- The energy loss becomes larger when the quark moving transverse to the anisotropy direction.
- The enhancement of the jet quenching parameters near critical temperature, as well as the drag force for a fast moving heavy quark, is observed, which is a typical feature of QCD phase transition.

Thanks!

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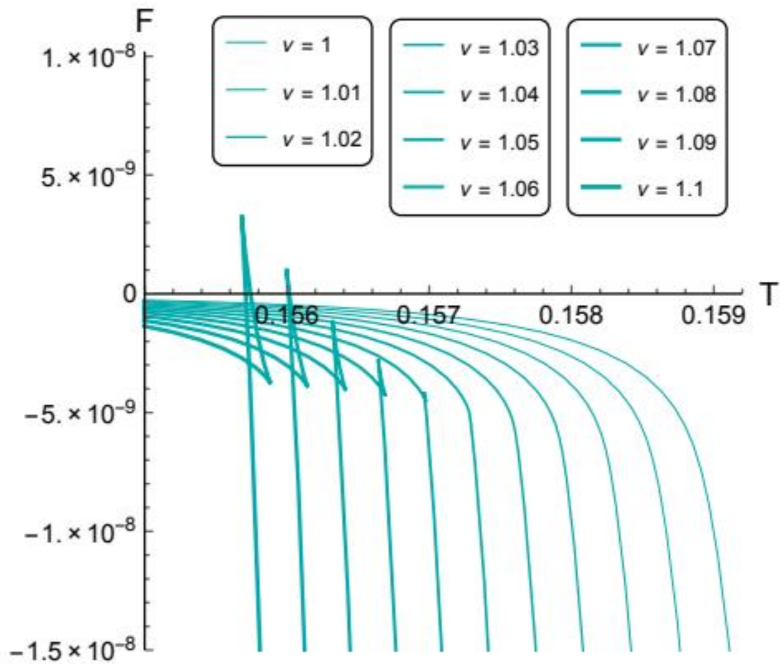

Figure 14. Free energy as function of temperature $F(T)$ for $\mu = 0$ in isotropic ($\nu = 1$) and slightly anisotropic ($\nu = 1.01,\ 1.02,\ 1.03,\ 1.04,\ 1.05,\ 1.06,\ 1.07,\ 1.08,\ 1.09,\ 1.1$) cases;

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Divergence at z=0 and its improvement

$$\phi' = \frac{1}{\nu z}\sqrt{\frac{3}{2}\,\nu^2 c^2 z^4 - 9\nu^2 c z^2 + 4\nu - 4}.$$

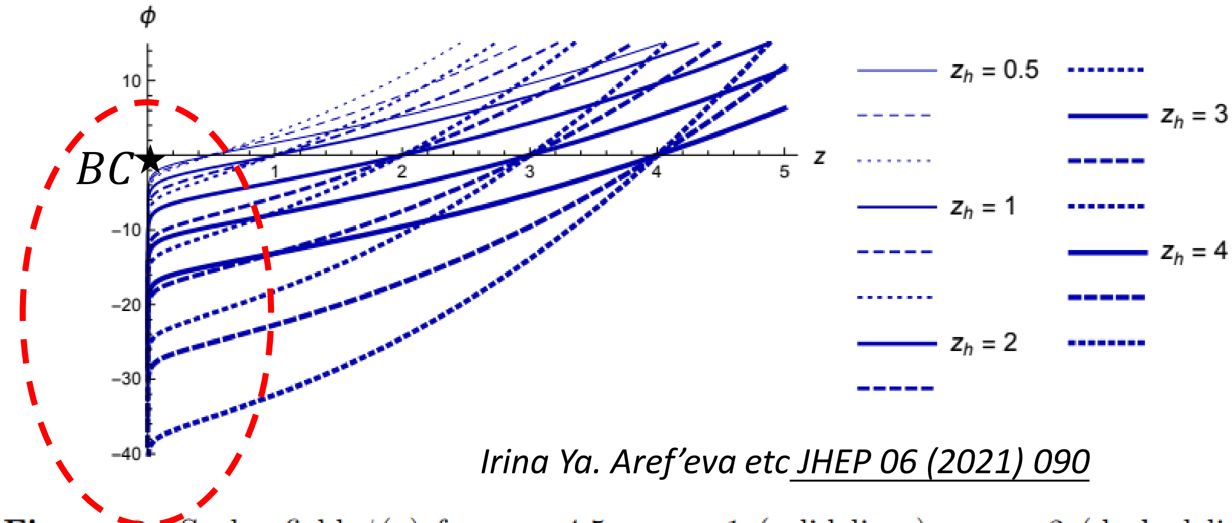

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Figure 3. Scalar field $\phi(z)$ for $\nu = 4.5$, $c = -1$ (solid lines), $c = -2$ (dashed lines) and $c = -3$ (dotted lines) and different z_h.