Thermal Transport and Energy Loss in Non-critical Holographic QCD

Umut Gürsoy

University of Utrecht

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U.G., E. Kiritsis, F. Nitti, G. Michalogiorgakis arXiv:0906.1890
U.G., E. Kiritsis, F. Nitti, L. Mazzanti arXiv:0903.2859
U.G., E. Kiritsis, F.Nitti arXiv:0707.1349
U.G., E. Kiritsis arXiv:0707.1324

QCD at high Temperature

- QCD at extreme conditions, vital to understand our universe.
- RHIC (Au + Au) probes QCD about 200-300 MeV with $\sqrt{s} = 200$ GeV per nucleon.
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- HOLOGRAPHIC APPROACH IS VERY PROMISING!

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  - Crucial for non-trivial T-dependence in thermodynamic functions (E, S, F)
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- Various different energy scales coexist at RHIC: hard partons in the soup (with $p_\perp \gtrsim 2.5$ GeV from head-on collisions), very important probes!

iHQCD framework see Nitti's talk

- Gravitational dual of pure YM in 2∂ effective 5D non-critical string theory:

$$S = M_p^3 N_c^2 \int d^5x \sqrt{g} \left\{ R + \frac{(\partial\lambda)^2}{\lambda^2} - V(\lambda) \right\} + G.H.$$

- Running 't Hooft coupling $\lambda_t(E) \propto \lambda(r)$ (dilaton), $\Leftrightarrow$ $\mathrm{Tr}\, F^2$

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  In the UV: $V(\lambda) = v_0 + v_1\lambda + v_2\lambda^2 + \cdots$
  - Gaussian f.p. as $\lambda \to 0$ (UV) $\Rightarrow$ AdS, non-zero V_0.
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  In the IR: $V(\lambda) \to \lambda^{\frac{4}{3}}(\log\lambda)^{\frac{1}{2}}$ as $\lambda \to \infty$
  - Linear quark potential $V_{q\bar{q}} = \sigma_s L + \cdots$
  - Gapped and discrete glueball spectrum $m_n^2 \propto n$
  - First order deconfinement transition at non-zero T_c.

iHQCD Thermodynamics **U.G., Kiritsis, Mazzanti, Nitti '08**

Two solutions with same asymptotics: $ds^2 = e^{A(r)}\left(dt^2 f(r) + dx_3^2 + \frac{dr^2}{f(r)}\right)$

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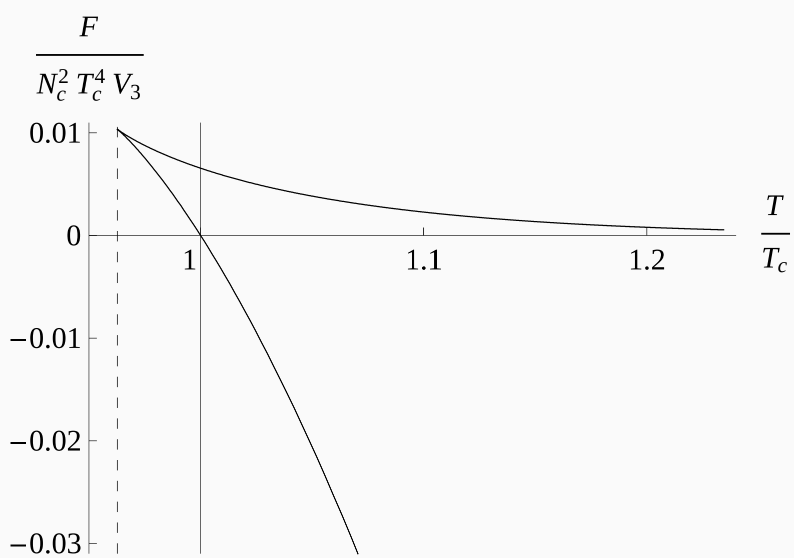
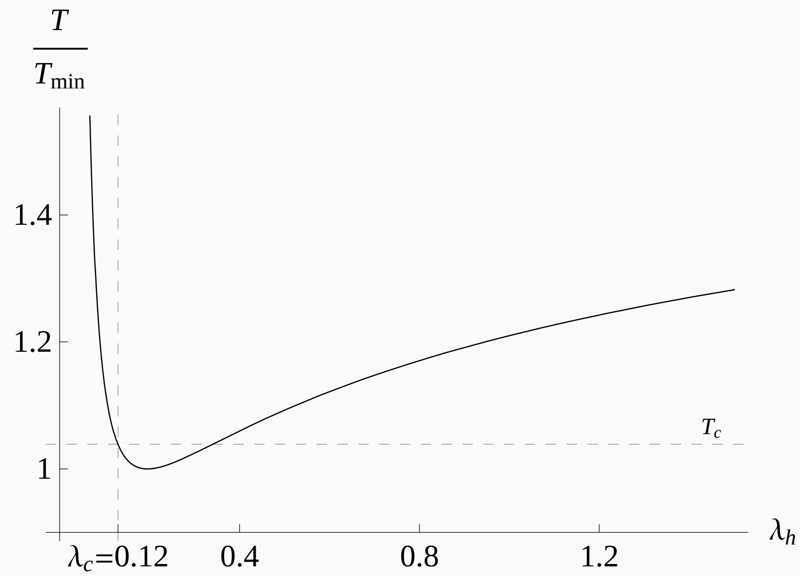
Free energy from $S_{BH} - S_{TG}$:





- Big and Small black-hole solutions, like $\mathcal{N} = 4$ on R^3

Survey of thermodynamical quantities I

- Fix the dilaton potential:

  $$V = \frac{12}{\ell^2}\left\{1 + V_0\lambda + V_1\lambda^{4/3}\log\left(1 + V_2\lambda^{\frac{4}{3}} + V_3\lambda^2\right)^{\frac{1}{2}}\right\}$$

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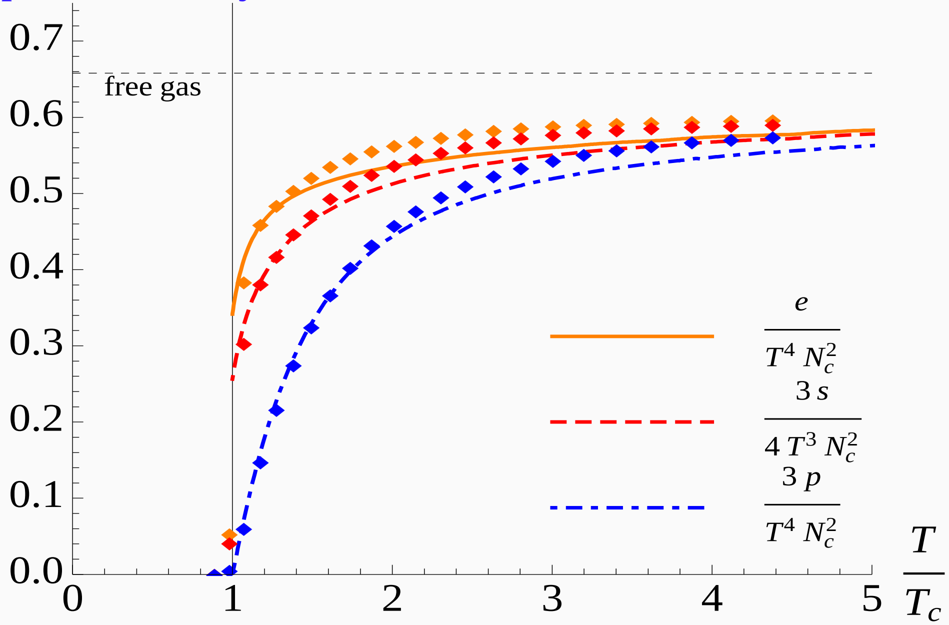
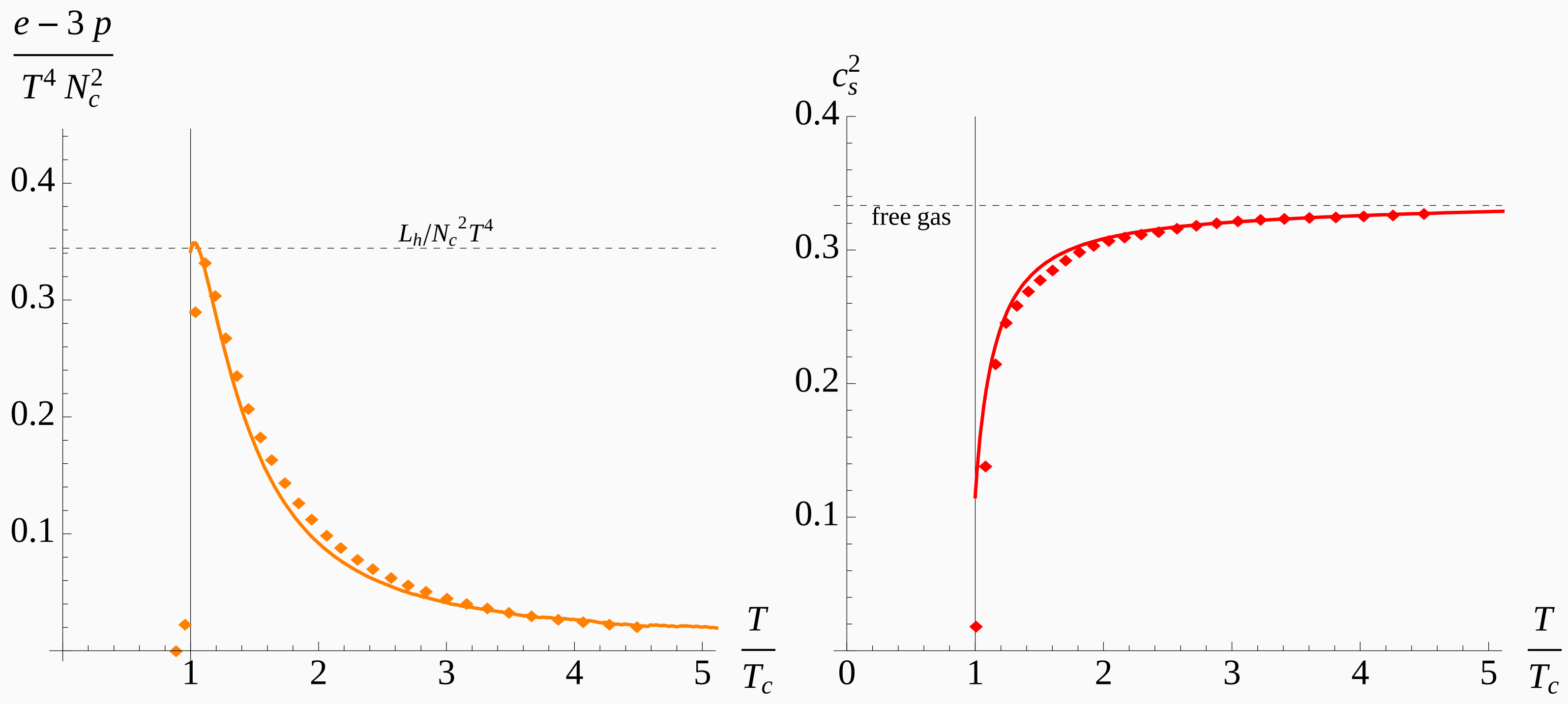


Survey of thermodynamic quantities II

Comparison to Boyd et al. '96

- The conformal anomaly and the speed of sound:



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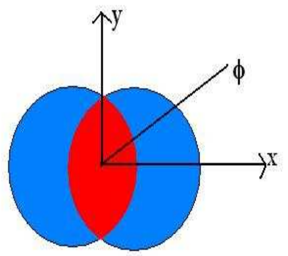

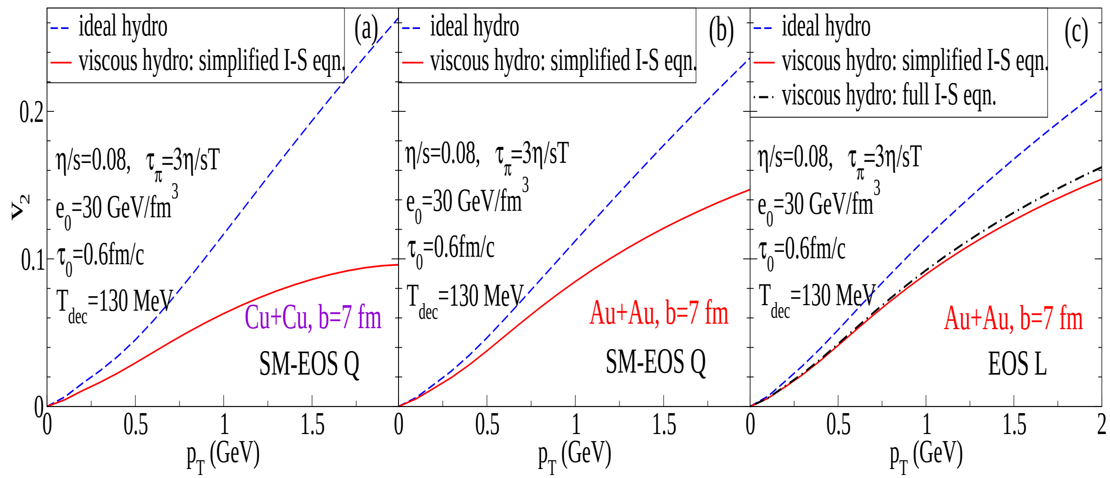

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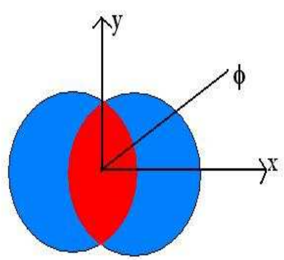

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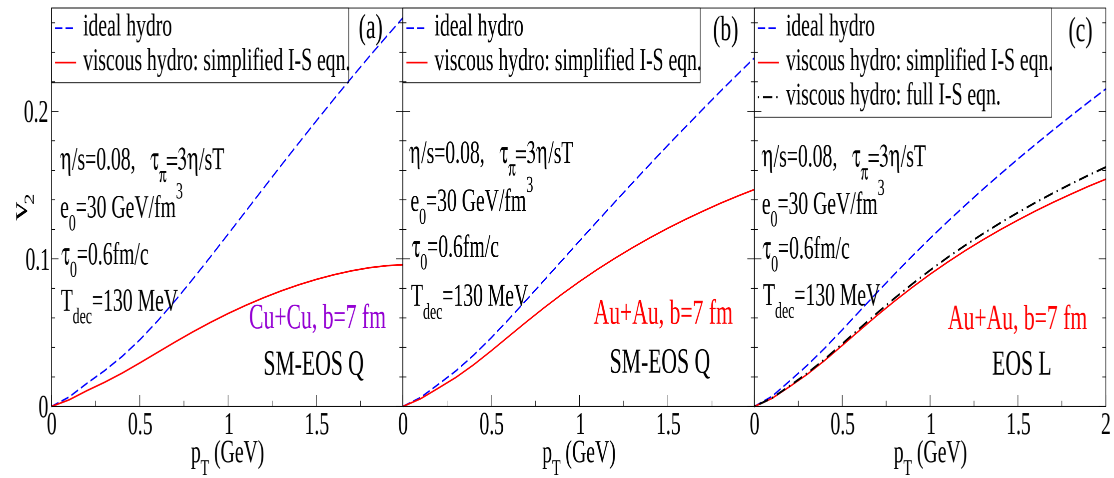

Finite Shear viscosity η/s: smaller v_2, flatter hadron spectra

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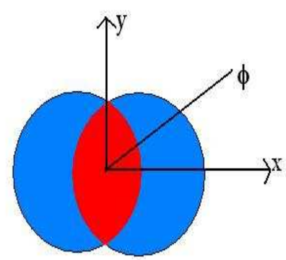

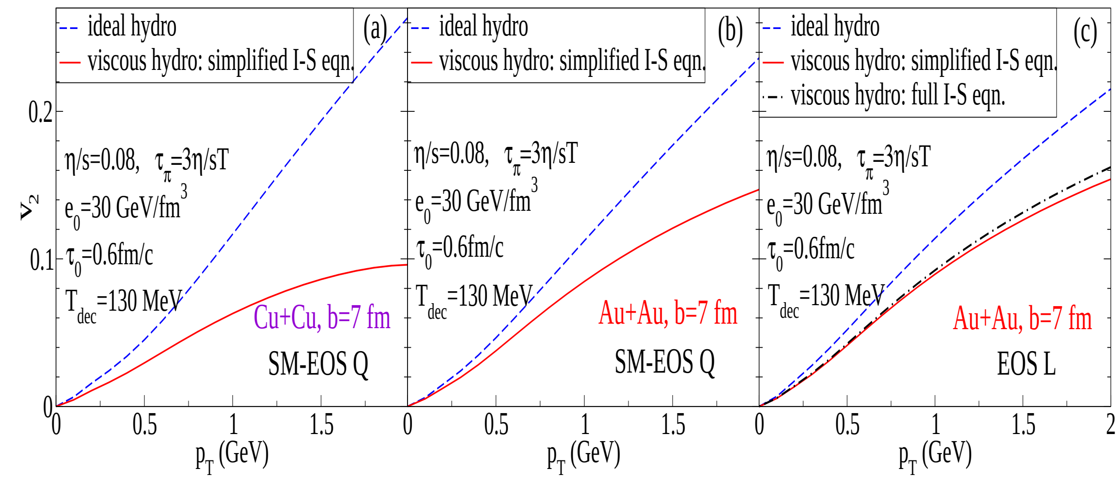

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Simulations vs. RHIC data: $\frac{\eta}{s} \approx 0.08–0.2$

In all 2∂ effective holography $\frac{\eta}{s} = \frac{1}{4\pi} \approx 0.08$!

Bulk viscosity

Another characteristic parameter of the fluid is the bulk viscosity, ζ:

$$T_{\mu\nu} = (\epsilon + p)u^{\mu}u^{\nu} + pg^{\mu\nu} - P^{\mu i}P^{\nu j}\left[\eta\left(\partial_i u_j + \partial_j u_i - \frac{2}{3}g_{ij}\partial\cdot u\right) + \zeta g_{ij}\partial\cdot u\right]$$

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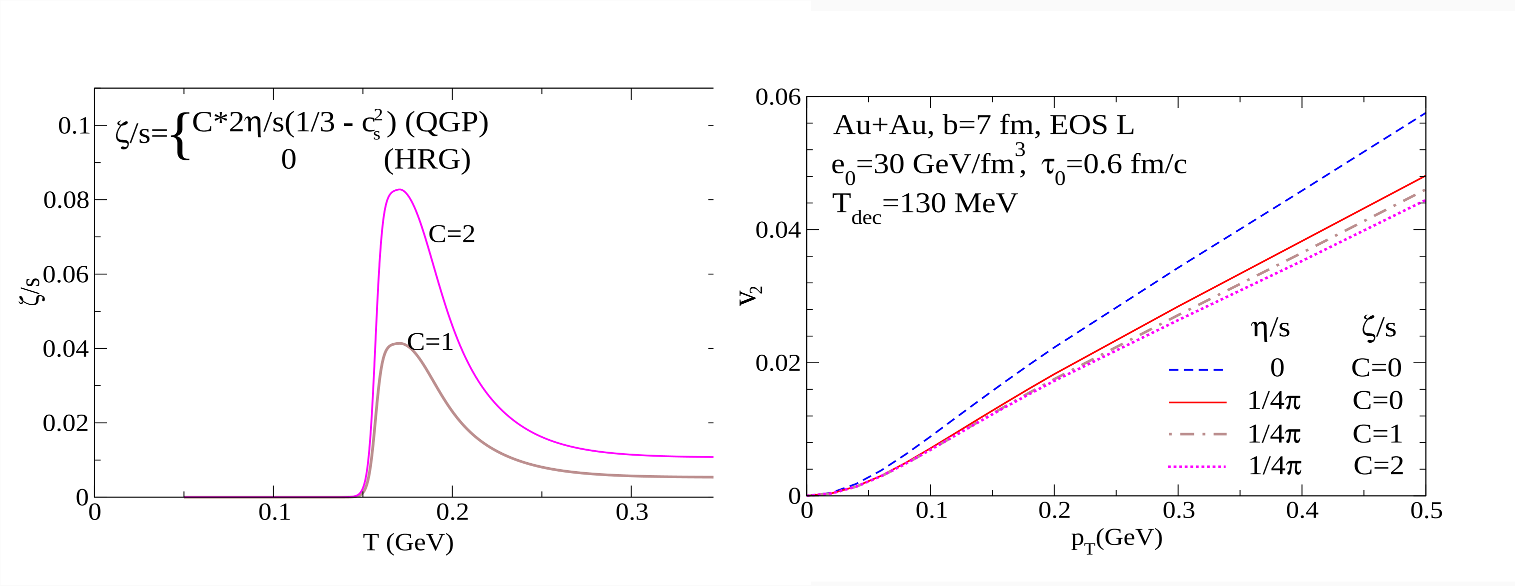

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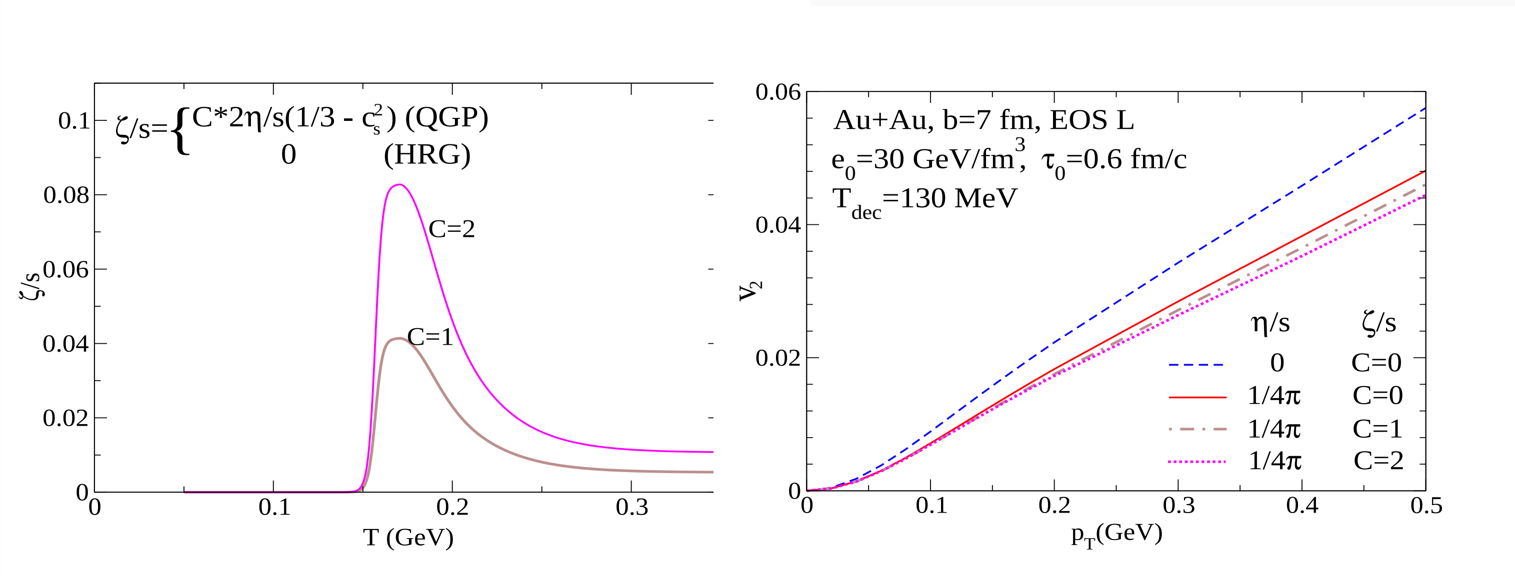

- Do we see similar behavior in our model?
- If so, what is the holographic reason for the rise near T_c?
- How significant is ζ near T_c? (Important to determine η)

Holographic computation

- Kubo's linear response theory: $\zeta = -\frac{1}{9}\lim_{\omega\to 0}\frac{1}{\omega} Im G_R(w,0)$ where $G_R(w,\vec{p}) = -i\int d^3x dt e^{i\omega t - i\vec{p}\vec{x}}\theta(t)\sum_{i,j=1}^{3} < [T_{ii}(t,\vec{x}), T_{jj}(0,0)] > .$
- Holography: $Im\, G_R \Leftrightarrow$ Flux of isotropic gravitons absorbed at the horizon $\propto h_{11}^{*} h_{11}' - h_{11} h'^{*}_{11}$.
- Derive the fluctuation equations for h_{ij}, pick up the gauge $\delta\phi = 0$,
- Fluctuations decouple in the smart gauge! Gubser et al '08: $\mathcal{F}(h_{11}'', h_{11}', h_{11}) = 0$.
- Boundary conditions:
  - $h_{11}(\phi = -\infty) = 1$ and,
  - In-falling wave at horizon $h_{11} \to c_b(\phi_h - \phi)^{-\frac{i\omega}{4\pi T}}$
- Read off $c_b(\omega, T)$

Results

Comparison with Meyer ’08

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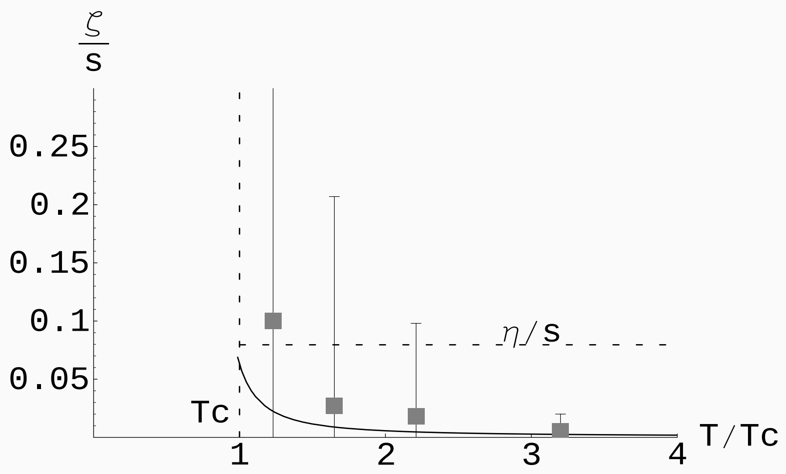

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- Near T_c Peak, smaller than lattice expectations!

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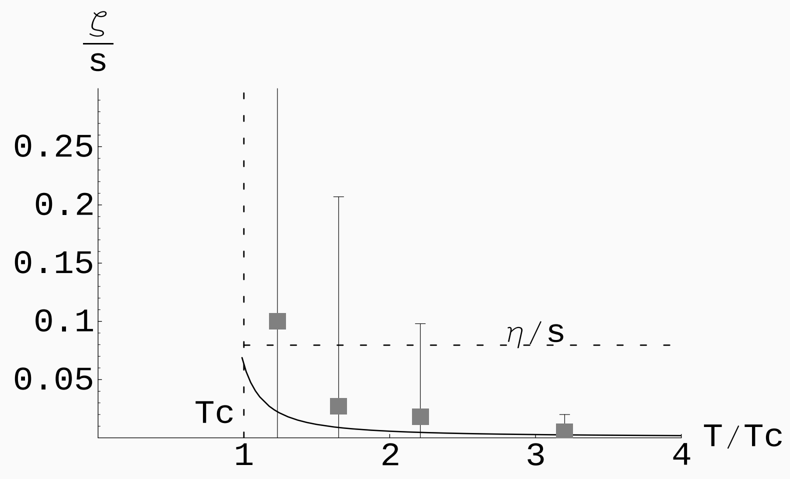

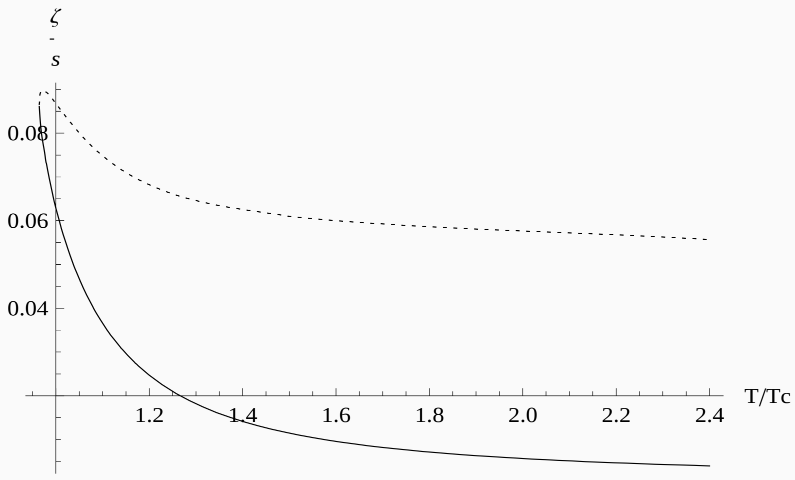

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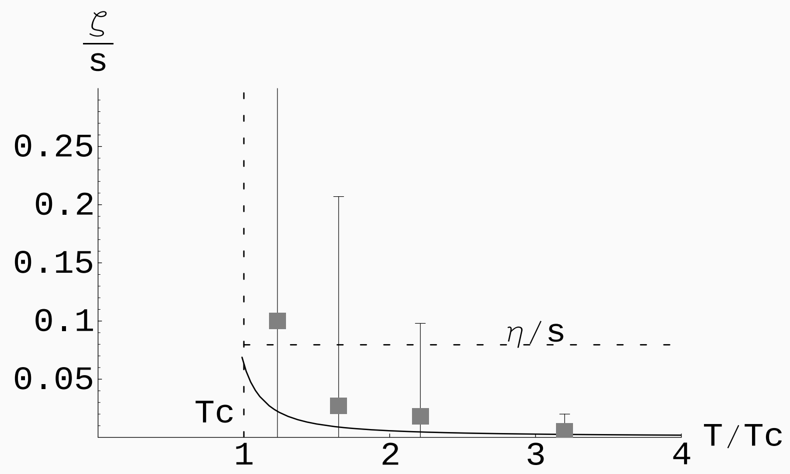

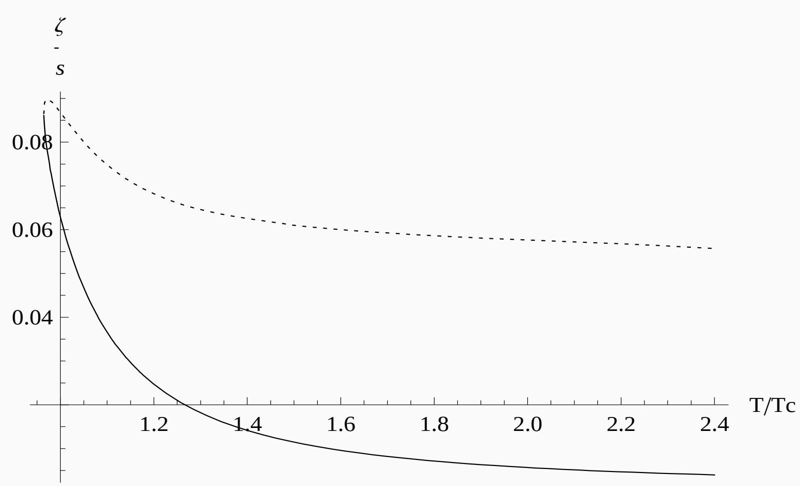

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  Gubser et al. 08
- Holographic explanation of the rise: due to small BH branch!
- Color confinement in zero-T theory $\Leftrightarrow$ peak near T_c at finite T! U.G, Kiritsis, Nitti, Mazzanti ’08

Energy loss of a heavy quark

- Highly energetic partons produced in head-on nuclei collisions are very important probes
- Example: When $m \gg \sqrt{\lambda} T$ a heavy quark moving the plasma , e.g. charm with $m = 1.4 \, GeV$
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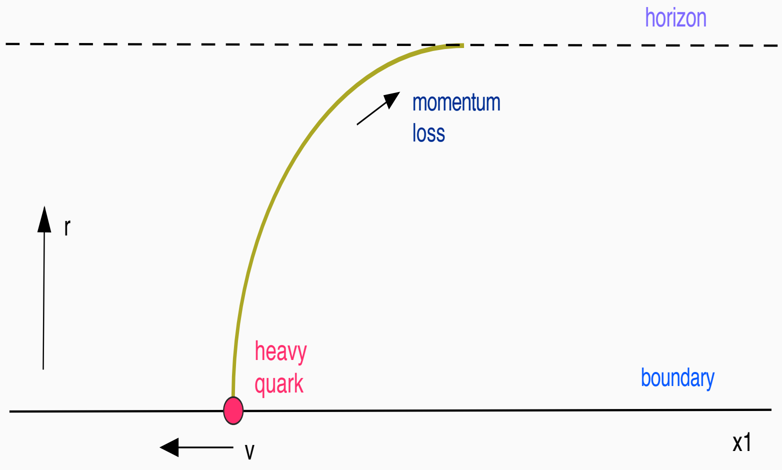
  equilibration time $\tau_e \gg \tau_{QGP}$
- In weakly coupled QGP: main shource of energy loss is collisions with thermal gluons and quarks.

  D. Teaney '03
- What happens in a strongly coupled plasma?

Holographic computation

Herzog et al; Gubser ’06

Holography: Represent the (infinitely) heavy quark with a trailing string moving with constant v:



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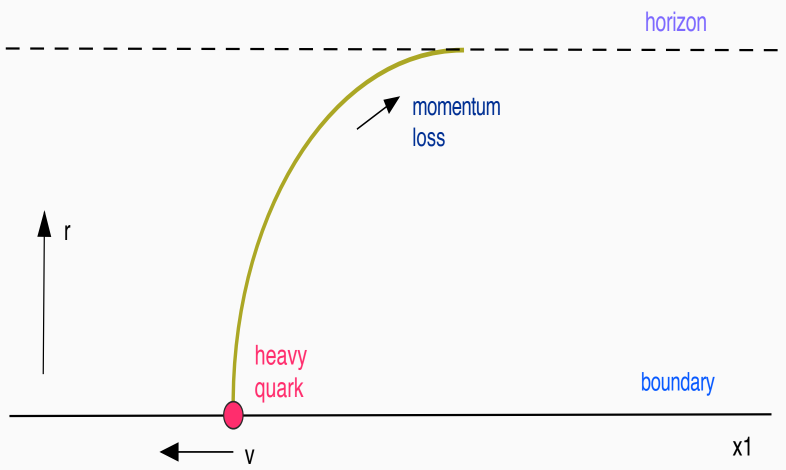

Drag force on a heavy quark in a hot wind:

$$F = \frac{dp}{dt} = \frac{1}{v}\frac{dE}{dt} = -\mu p + \zeta(t)$$

Ignore stochastic force $\zeta(t)$ in this talk $\Leftrightarrow$ fluctuations of the trailing string $\Rightarrow$ diffusion constant.

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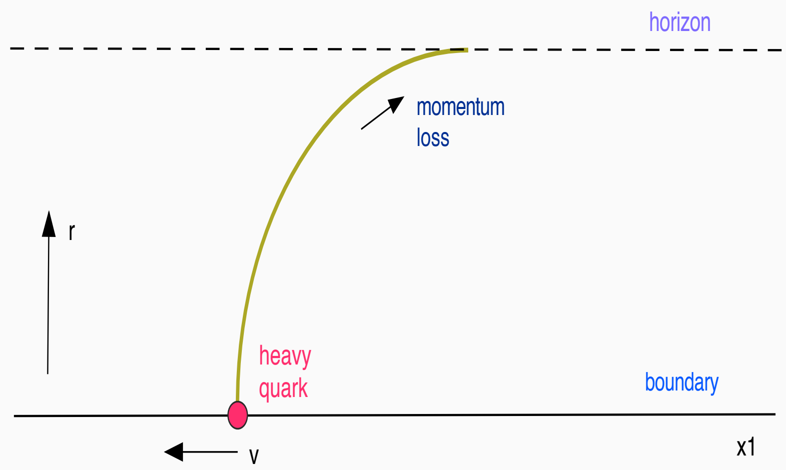

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What is μ? What is τ_e at strong coupling?

Results: Energy loss

Standard calculation:

$F = \frac{1}{v}\frac{dE}{dt} = -\frac{1}{2\pi\ell_s^2}\ v\ e^{2A(r_s)}\lambda(r_s)^{\frac{4}{3}}$, r_s defined by $f(r_s) = v^2$.

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Relativistic limit, $v \to 1$: $F = -\frac{\ell^2}{\ell_s^2}\sqrt{\frac{45\; Ts(T)}{4N_c^2}}\frac{v}{\sqrt{1-v^2}\left(-\frac{\beta_0}{4}\log\left[1-v^2\right]\right)^{\frac{4}{3}}} + \cdots$

Non-relativistic limit $v \to 0$: $F = -\frac{\ell^2}{\ell_s^2}\left(\frac{45\pi\; s(T)}{N_c^2}\right)^{\frac{2}{3}}\frac{\lambda(r_h)^{\frac{4}{3}}}{2\pi}v + \cdots$

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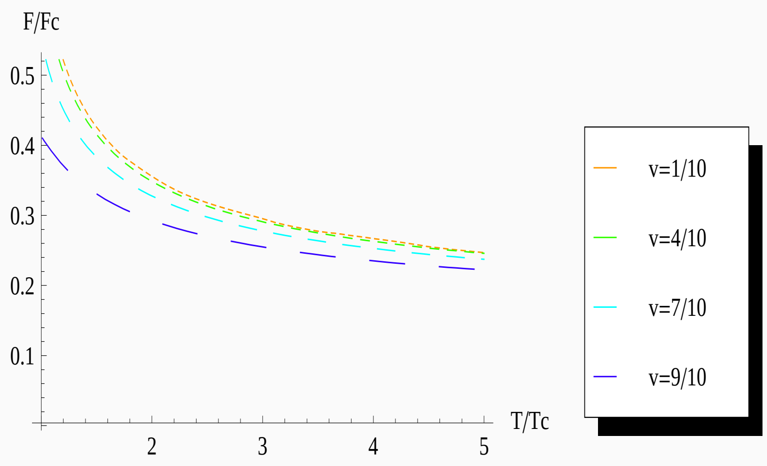
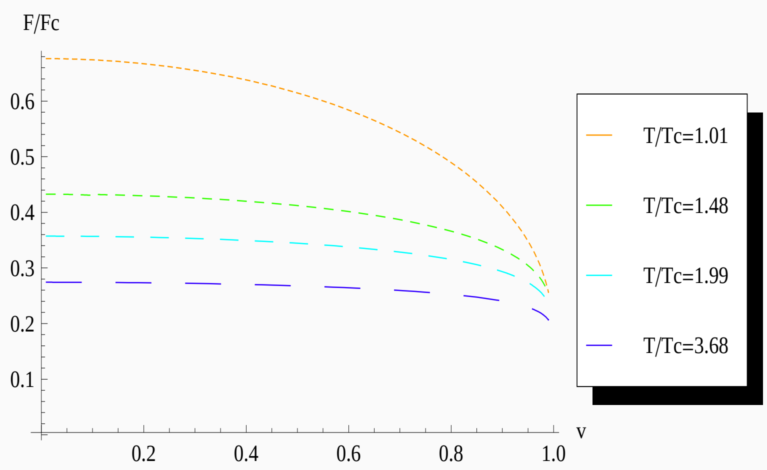
Compare with the AdS result: $F_{conf} = \frac{\pi}{2}\sqrt{\lambda}T^2\frac{v}{\sqrt{1-v^2}}$





Results: Equilibration time

$F = -\frac{p}{\tau_e(p)}$ In the conformal case: $\tau_{conf} = \frac{2m_q}{\pi\sqrt{\lambda}T^2}$, independent of p.

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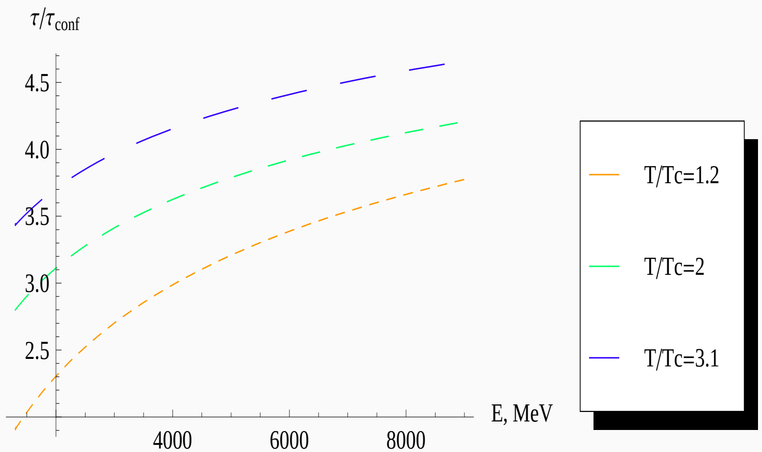
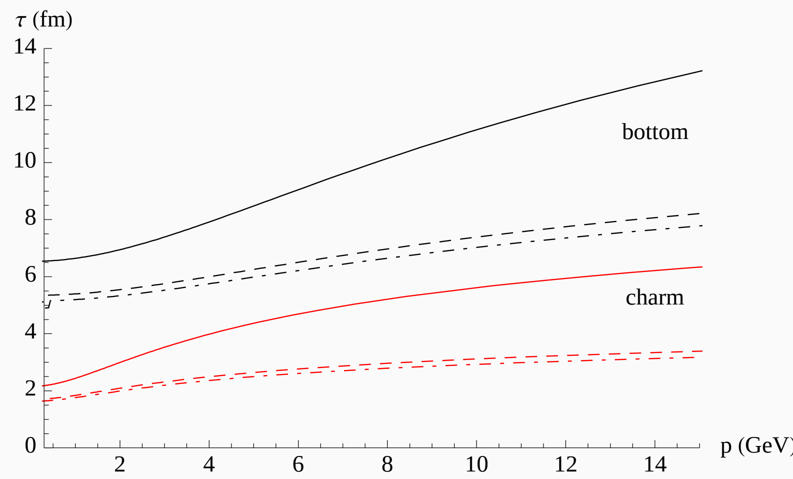


Result for charm and bottom

$T_{QGP} = 250\ MeV$



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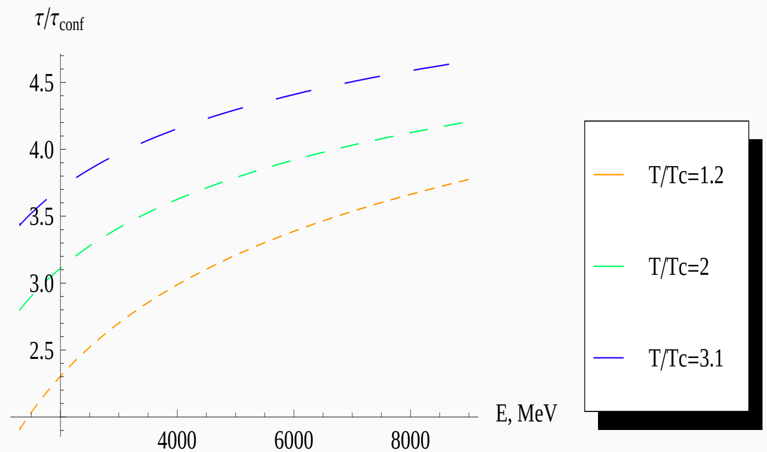

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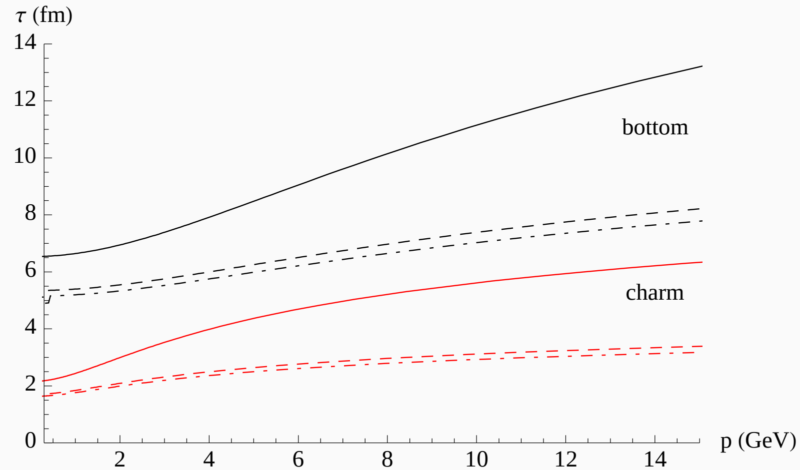

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Direct (solid): $T_{QGP} = T_{our}$

Alternative: $E_{QGP} = E_{our}$ (dashed), $s_{QGP} = s_{our}$ (dash-dotted)

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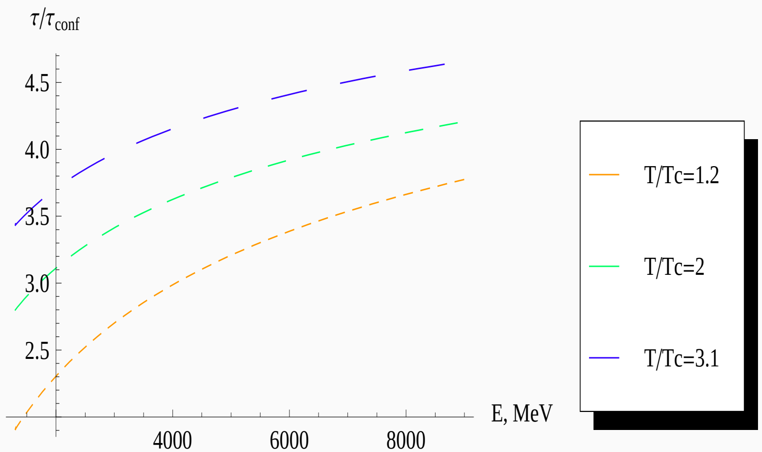

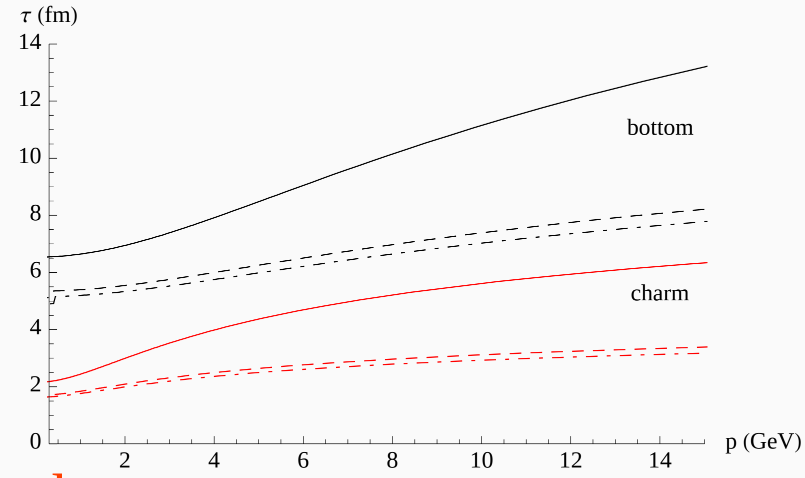

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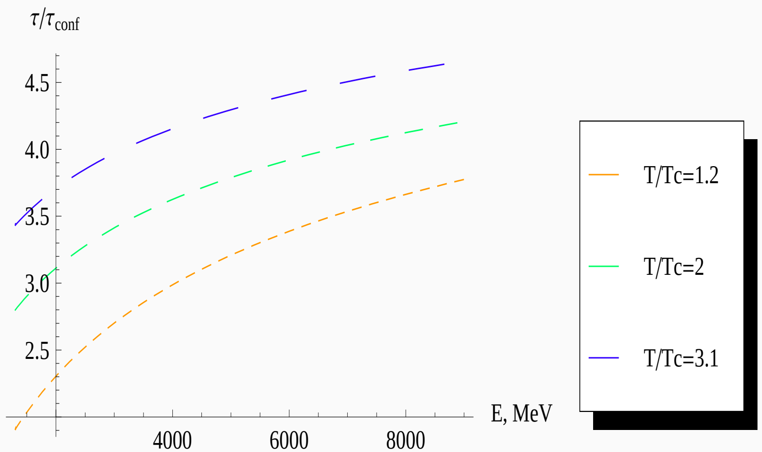

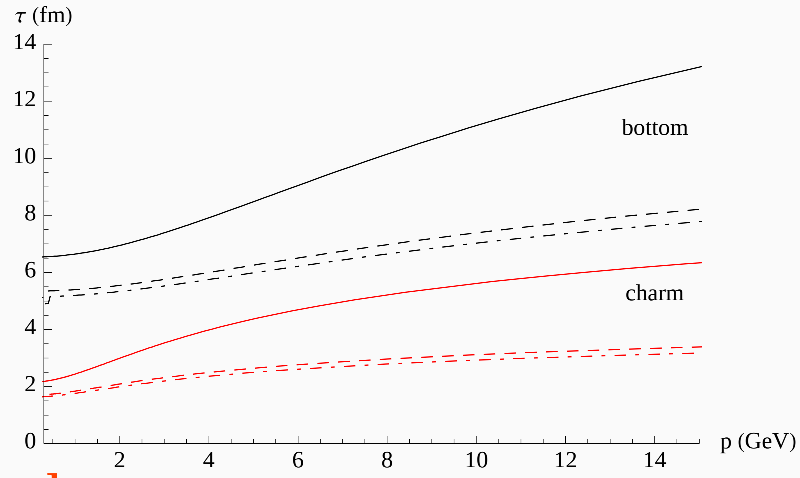

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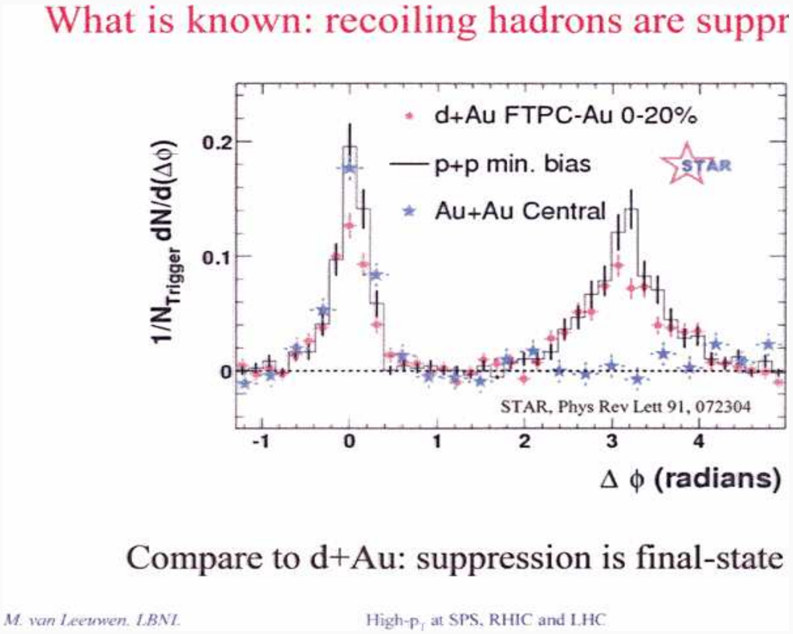
$\tau_e \approx 4.5\ fm$ (charm) $\Rightarrow$ BETTER THAN ADS CASE!

Jet quenching

Back-to-back jet production is highly suppressed at RHIC:



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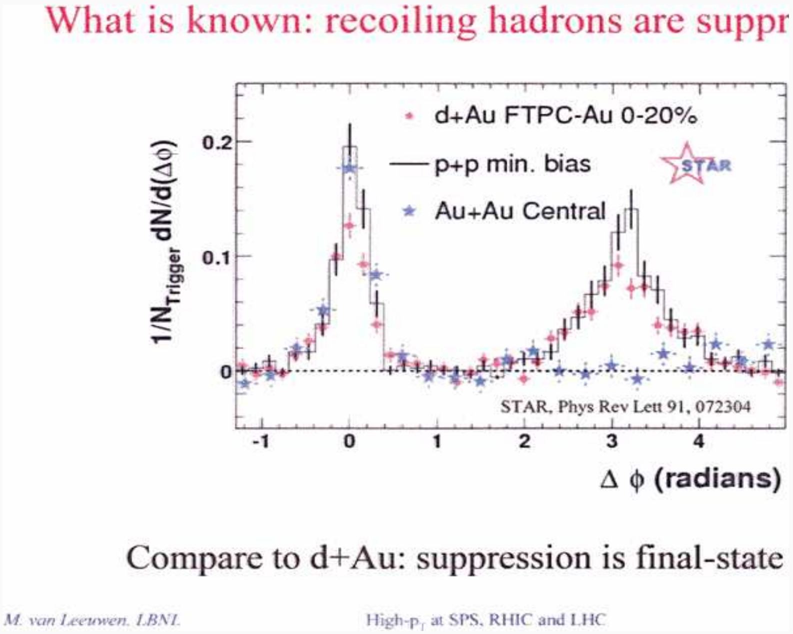

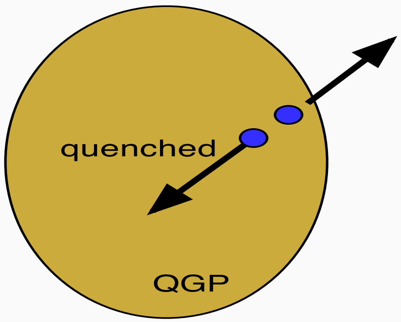

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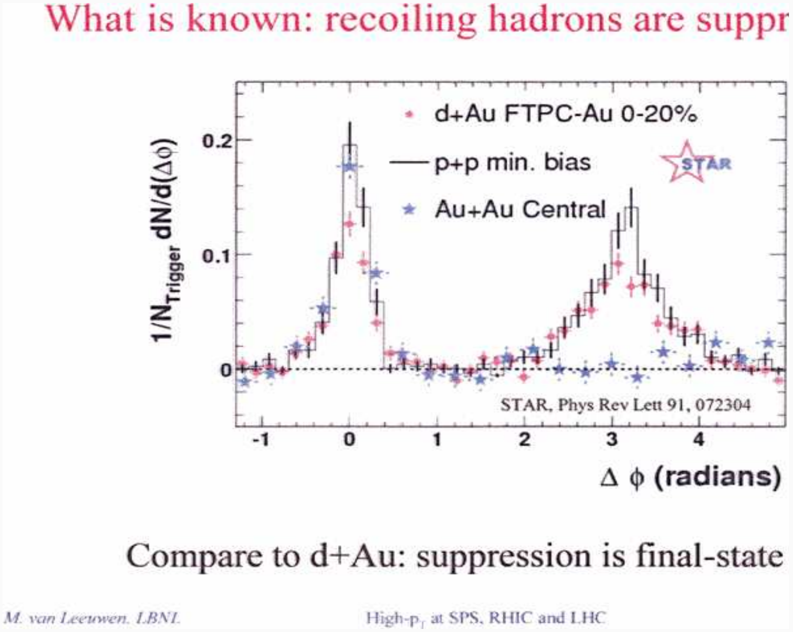
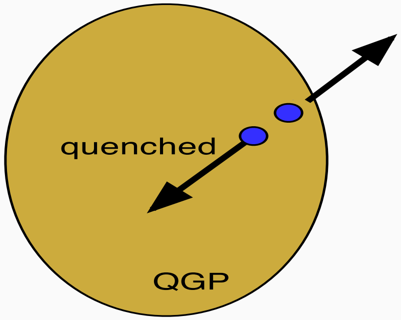




Jet-quenching parameter Baier et al ’96

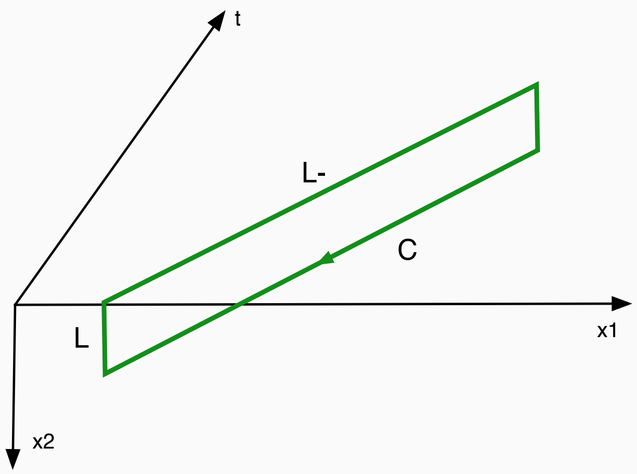
Average transverse momentum lost into the media in a flight of distance D.

Main source of energy loss is gluon Brehmstrahlung.

Weak-coupling computation comes too short in explaining the data.

Jet quenching, non-perturbative

Non-perturbative def. of $\hat{q}$:



Wiedemann '00

$$\langle W(C)\rangle \approx \exp\left[-\frac{1}{8\sqrt{2}}\hat{q}L^{-}L^{2}\right].$$

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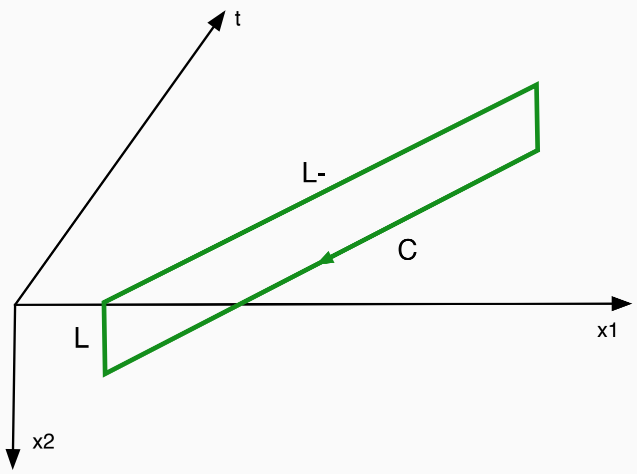

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Holographic computation Liu, Rajagopal, Wiedemann '06: $\langle W(C)\rangle = e^{iS}$

Pick up gauge: $x^{-} \equiv x_1 - t = \tau$, $x_2 = \sigma$, Compute minimal area:

- $\hat{q} = \frac{\sqrt{2}}{\pi \ell_s^2} \frac{1}{\int_0^{r_h} \frac{dr}{e^{2A_s}\sqrt{f(1-f)}}}$

Results

T_{QGP}, MeV	$\hat{q}\ (GeV^2/fm)$ (direct)	$\hat{q}\ (GeV^2/fm)$ (energy)	$\hat{q}\ (GeV^2/fm)$ (entropy)
220	-	0.89	1.01
250	0.53	1.21	1.32
280	0.79	1.64	1.73
310	1.07	2.14	2.21
340	1.39	2.73	2.77
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Close to AdS somewhat smaller than pQCD + fit to data Eskola et al '05

$$\hat{q}_{expect} \sim 5 - 12\ GeV^2/fm$$

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