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Far-from-equilibrium energy loss

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Introduction

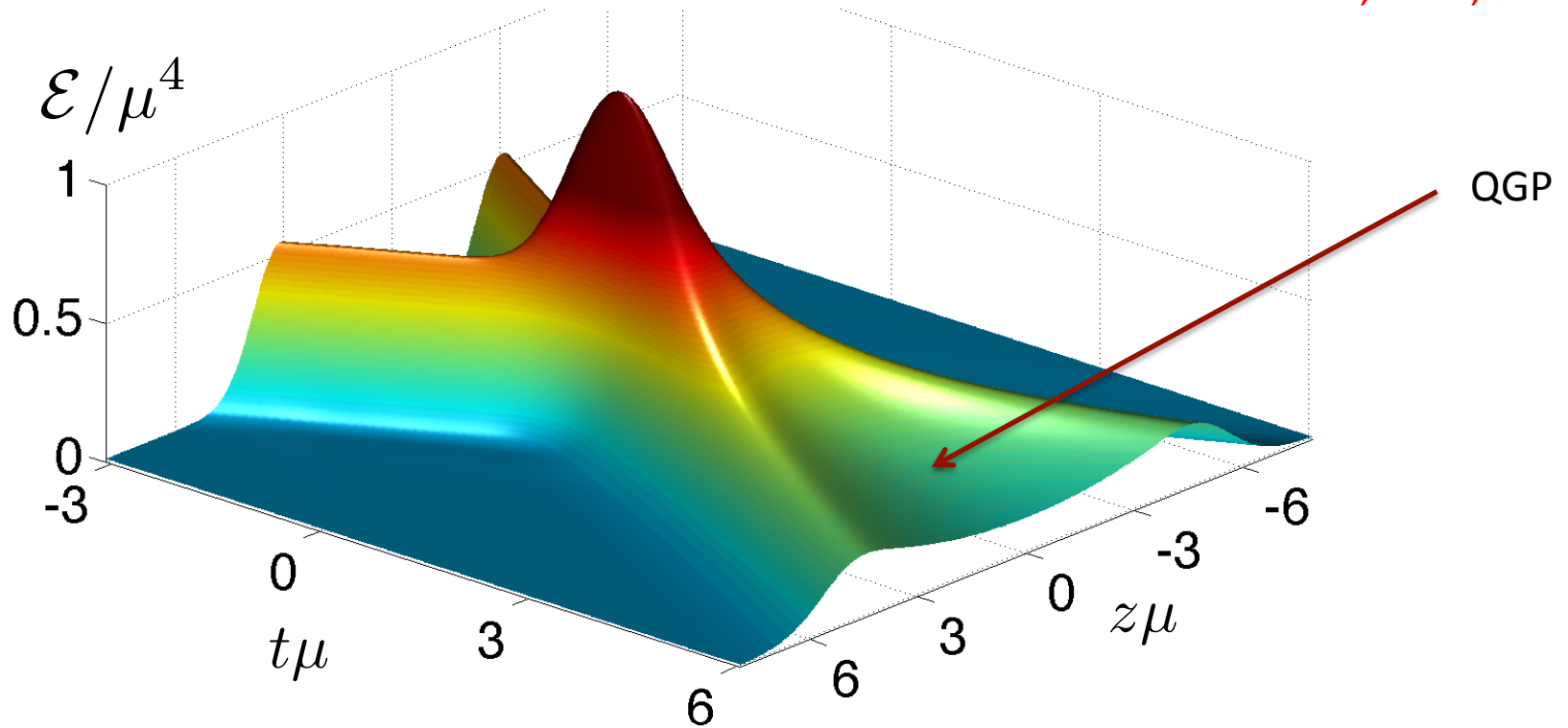
- ✦ Parton energy loss in heavy ion collisions is one of the most important Hard Probes of the QGP.
- ✦ But, how much energy do hard partons lose early – in the pre-equilibrium, pre-QGP, epoch of the collision?
- ✦ Most approaches to the pre-equilibrium epoch assume that physics then is weakly coupled.
- ✦ At least as a benchmark against which to compare, can we answer **this question** upon assuming that physics is strongly coupled throughout the collision?

Short intro to holographic principle

- ✦ **Holography** (aka AdS/CFT correspondence) is for now the only tool we have to get insights about strongly coupled far-from-equilibrium physics.
- ✦ (Over-)Simplified definition of **holographic principle** – dynamics of the strings in 5-dim space-time describes the motion of its end-point(s) – quark(s) living on the boundary 4-dim space-time.
- ✦ We compute the energy loss of a quark moving through the pre-plasma, far-from equilibrium, matter made when two sheets of energy collide in strongly coupled N=4 SYM theory (holographically, in asymptotically AdS₅ space-time).

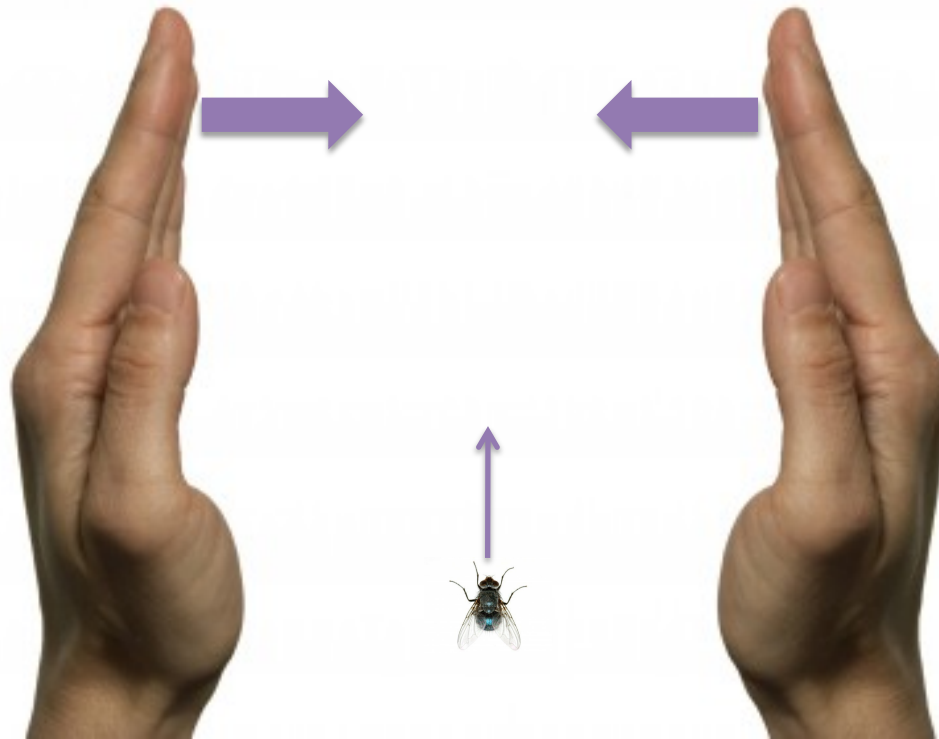
Colliding sheets

Chesler, Yaffe, 2010

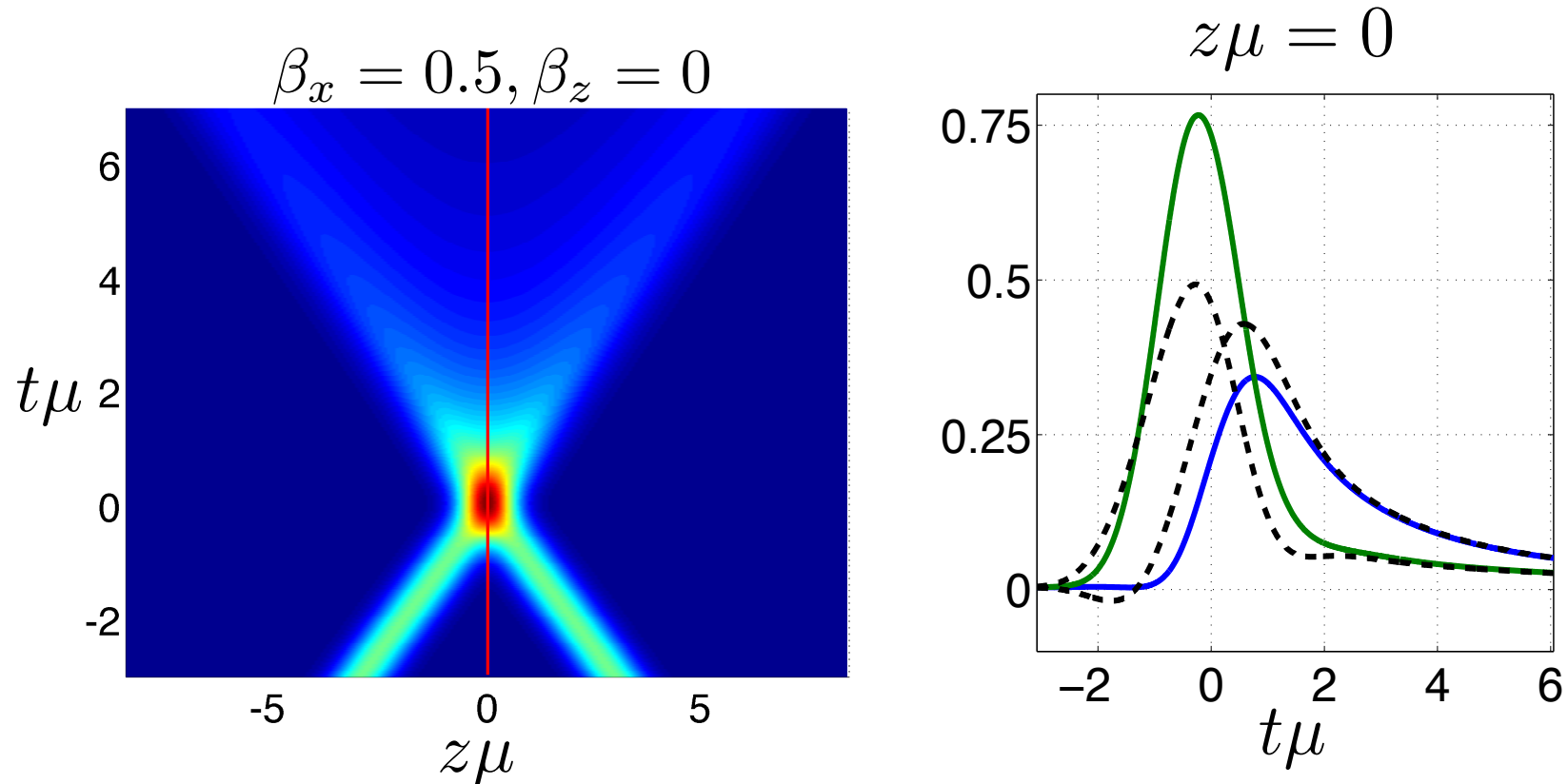


- ✦ Colliding planar shockwaves with Gaussian profile, with width $\sim 1/\mu$.
- ✦ Shocks collide at $t = 0$.
- ✦ Estimated energy scale for RHIC, $\mu \sim 2$ GeV.

Collision set-up



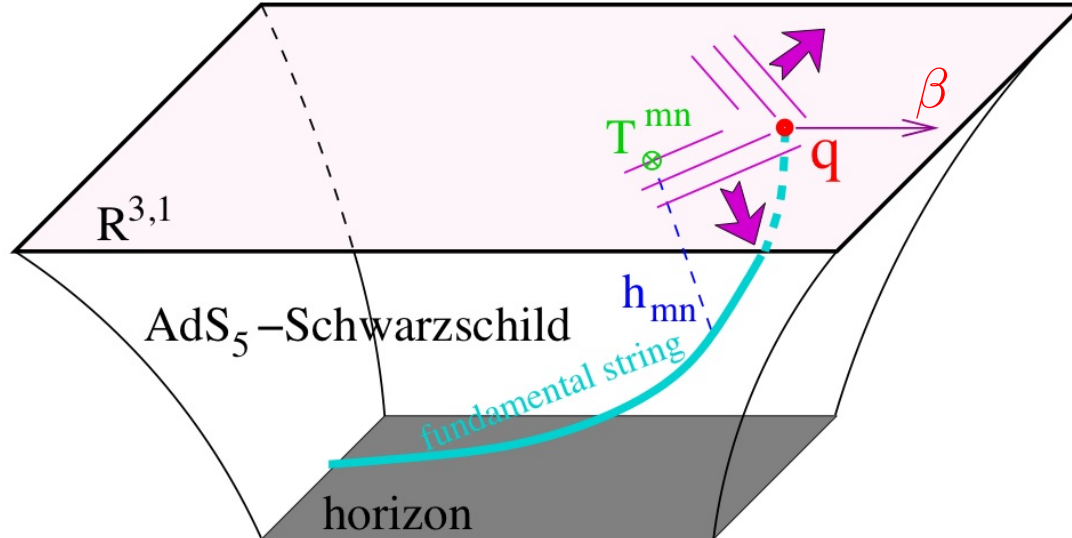
Colliding sheets, zero-rapidity case



- ✦ Parallel pressure peaks at around the collision time.
- ✦ Hydrodynamics become applicable at around $t_\mu = 2 - 3$ corresponding to about 3 sheet thicknesses after the collision.
- ✦ Parallel and transverse pressures still differ: viscous hydro (dashed lines).
- ✦ What is the force required to drag an infinitely massive quark along this path?

Dragged quark

- ✦ Heavy quark, being dragged through the medium with constant velocity β .
- ✦ If the medium is static plasma, **trailing string solution**:



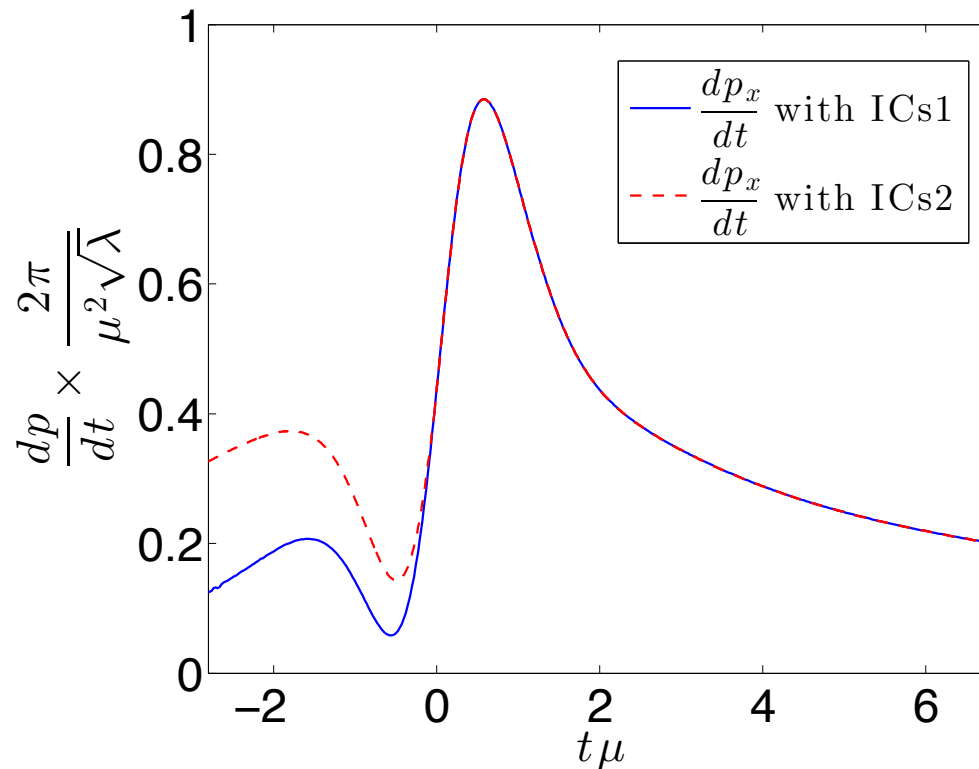
Herzog et al.; Gubser;
Casalderrey-Solana,
Teaney, 2006

$$\frac{dp}{dt} = -\frac{\sqrt{\lambda}}{2\pi} (\pi T)^2 \frac{\beta}{\sqrt{1-\beta^2}}$$

- ✦ What happens when the quark is being dragged through the colliding shocks? How does the drag force dp/dt compare to expectations based on static case?

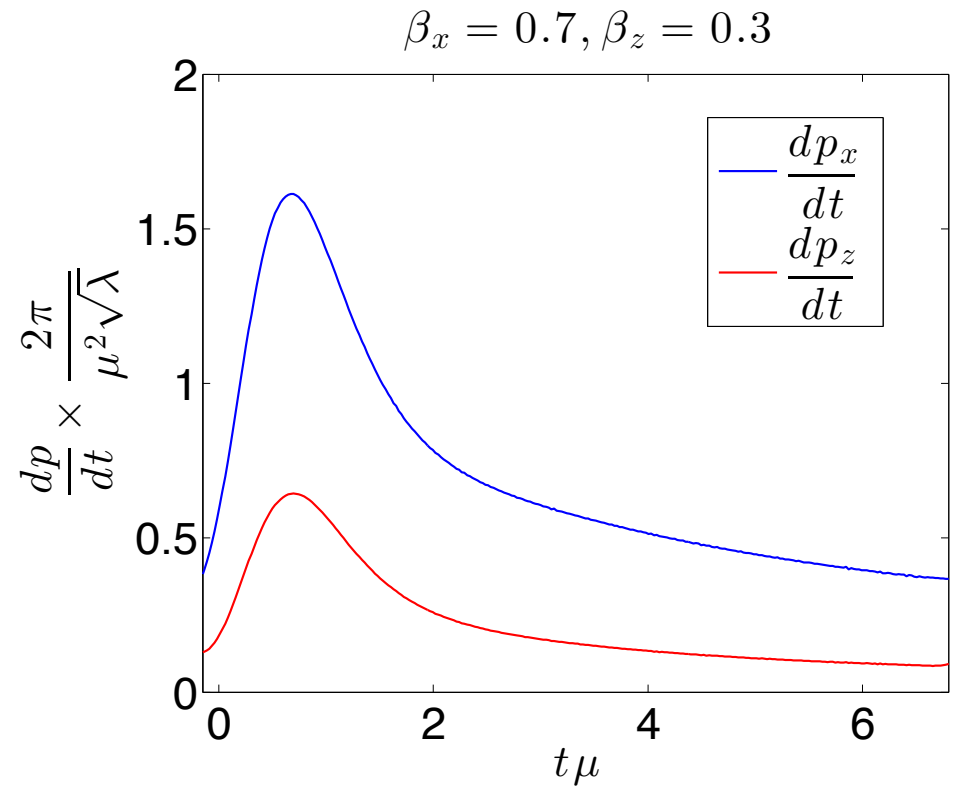
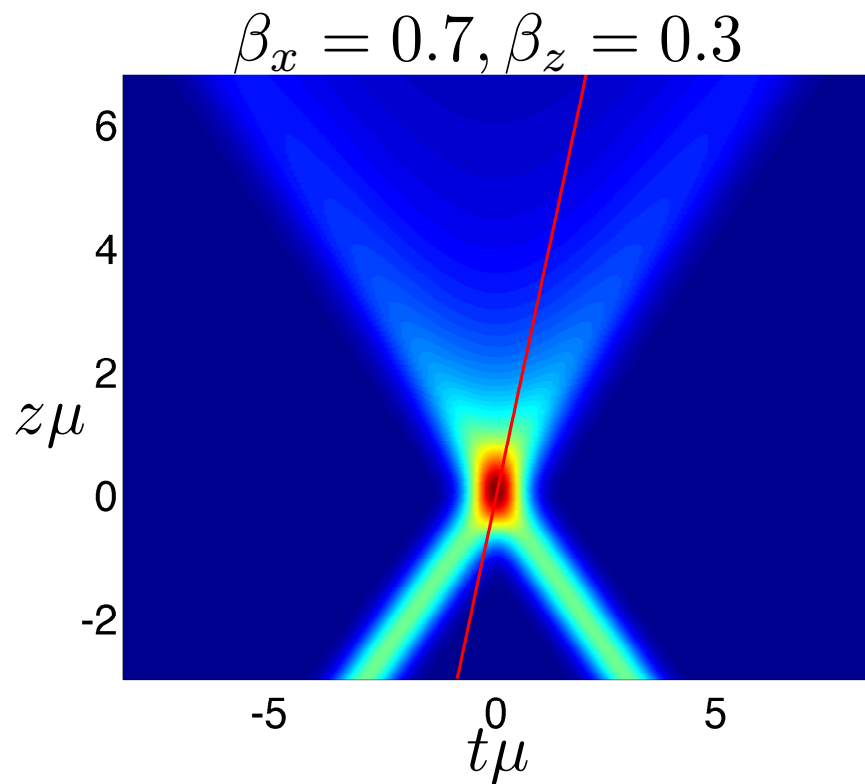
Zero-rapidity case

$$\beta_x = 0.5, \beta_z = 0$$



- ✦ Pre-collision force depends on the initial conditions of the string. (Work in progress.)
- ✦ After the collision, force is independent of the initial configurations.
- ✦ The force peaks slightly after the collision, at around $t\mu \sim 0.8$.
- ✦ The force is decreasing due to the continuing plasma expansion

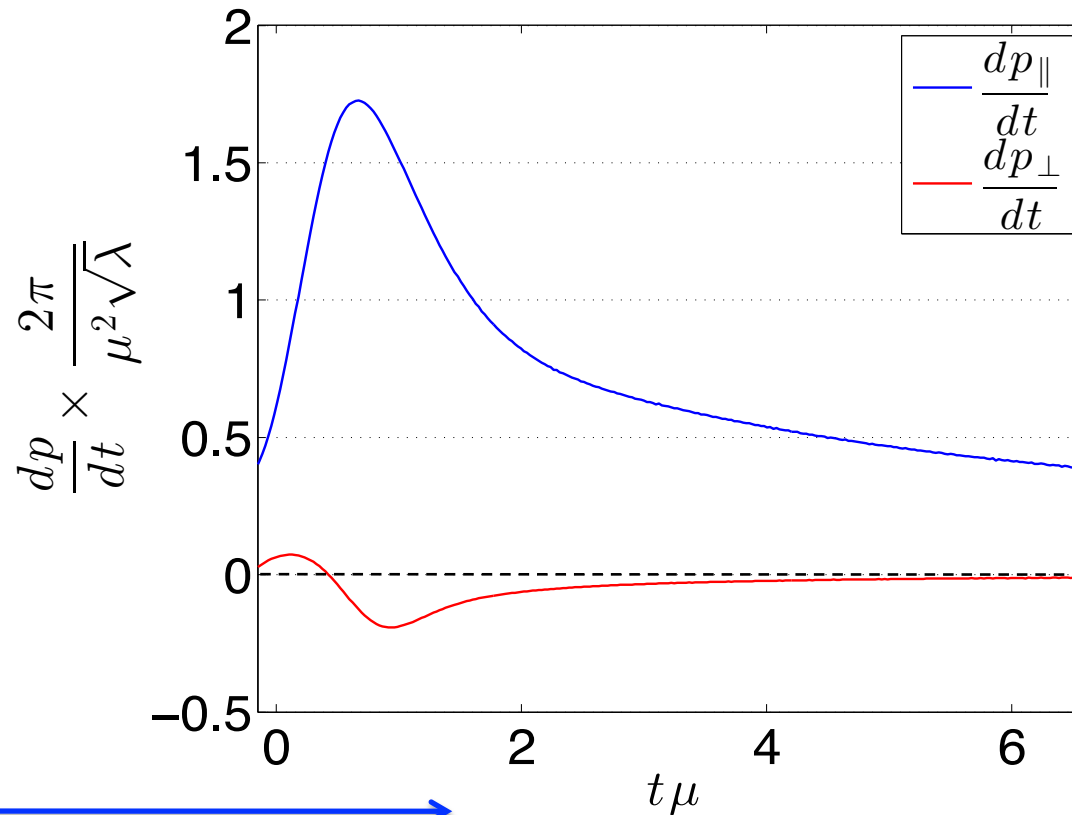
Non-zero-rapidity case



- ✦ Quark is dragged with non-zero parallel velocity
- ✦ Just like in the zero-rapidity case, the force peaks just slightly after the collision, at $t\mu \sim 0.8$

Local fluid rest frame

$\beta_x = 0.7, \beta_z = 0.3$. Fluid rest frame.



- ✦ Boosted to the local rest reference frame of the fluid.
- ✦ Non-zero force component perpendicular to the velocity of the quark in the local fluid rest frame – a consequence of the presence of velocity gradients.

Equilibrium Expectations

- ✦ We want to compare our results to drag force in an equilibrium plasma with the same instantaneous energy density, or transverse pressure, or parallel pressure.
- ✦ In the local fluid rest frame, extract “temperatures” from the energy density and pressure (transverse, parallel) using the equilibrium EoS.

$$T_{eq.}^{\mu\nu} = \frac{\pi^2 N_c^2 T^4}{8} \text{diag}(3, 1, 1, 1)$$

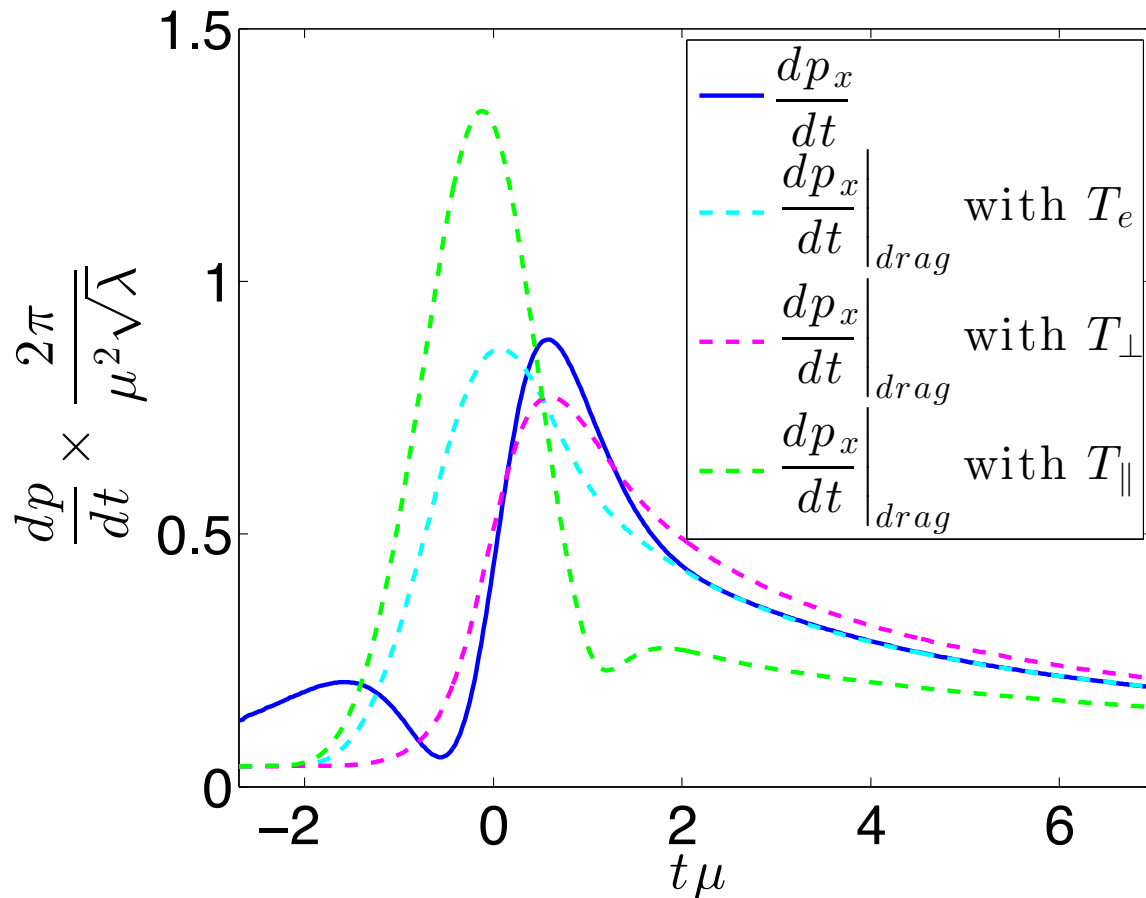
$$T_e^4 = T^{00} \frac{8}{3} \frac{1}{\pi^2 N_c^2}$$

$$T_{\perp}^4 = T^{\perp\perp} \frac{8}{\pi^2 N_c^2}$$

$$T_{\parallel}^4 = T^{zz} \frac{8}{\pi^2 N_c^2}$$

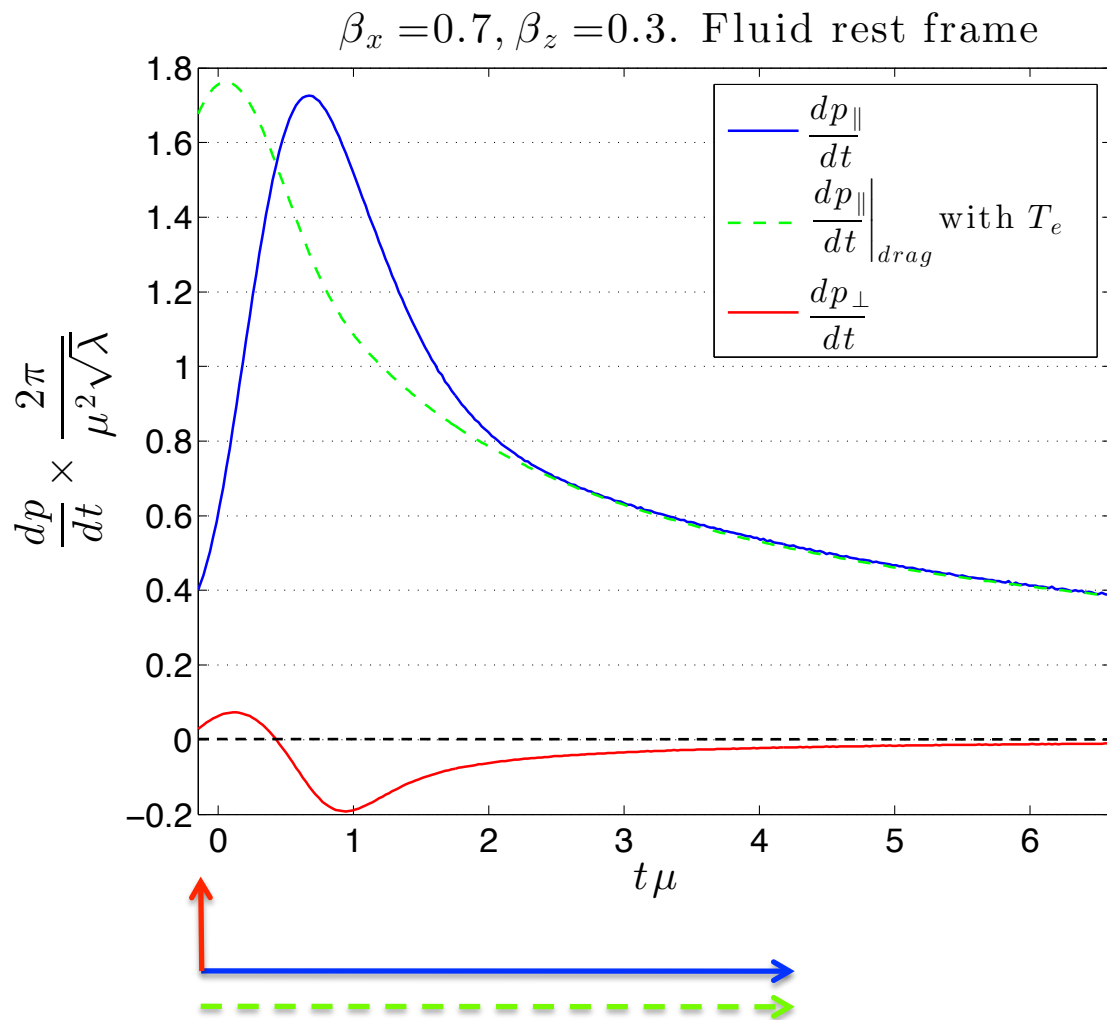
Zero-rapidity case

$$\beta_x = 0.5, \beta_z = 0$$



- ✦ Comparison to the force obtained from the equilibrium using temperatures associated with energy density and pressures.
- ✦ “Temperature” T_e associated with the energy density describes the drag force best for $t\mu > 2$.
- ✦ The force peaks at similar time as the static drag result associated with the transverse pressure.

Fluid rest frame



- ✦ Projecting the actual force along (**parallel**) and **perpendicular** to the velocity in the fluid rest frame.
- ✦ At late times, **parallel** component agrees with the **equilibrium expectation**, but there is an additional **perpendicular** component, approaching zero at late times.
- ✦ Presence of velocity gradients yields **perpendicular** component of the force, which of course is absent in **equilibrium expectation**.

Conclusions

- At late times, when system is in the thermal equilibrium:
 - Force acting against the motion (*i.e.*, energy loss) very well described by equilibrium drag with temperature T_e associated with the energy density in the local rest frame.
 - Additional small perpendicular force, if there are velocity gradients.
- At early times, just after the collision:
 - The force is comparable to equilibrium expectations. Closest to equilibrium drag with temperature obtained from transverse pressure in the local rest frame.
- Lessons to be learned:
 - No extraordinary pre-equilibrium energy loss mechanism. Equilibrium expectations are a good guide.
 - This calculation is an example of holographic calculations taking steps in the direction from static “bricks” of plasma toward realistic space-time evolution. Further steps are possible.