Theory of Jet Quenching: A phenomenological overview

Jorge Casalderrey Solana

MARIE CURIE ACTIONS

CERN

PEOPLE

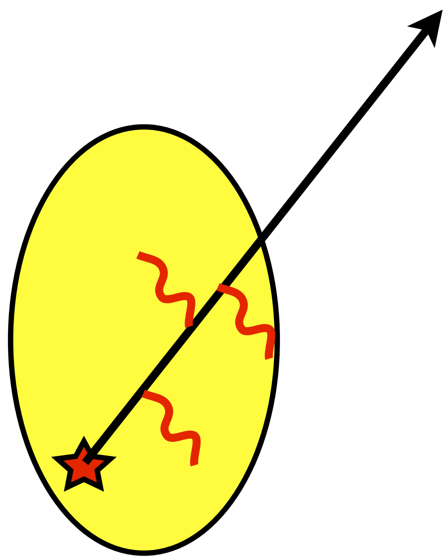
Jet Quenching: Weak vs Strong Coupling

Jorge Casalderrey Solana

Outline

- Motivation
- (Slow) Heavy Quark loss
  - Collision loss and Brownian motion
  - Lessons from AdS/CFT
- Energetic particles
  - Radiative energy loss
  - Energetic particles in AdS/CFT
  - Quenching
- Medium backreaction
  - Phenomenology of conical flow
  - Sound emission in AdS/CFT

Hard Probes and HIC



$$\tau_{from} \sim \frac{1}{p_T}, \frac{1}{M}$$

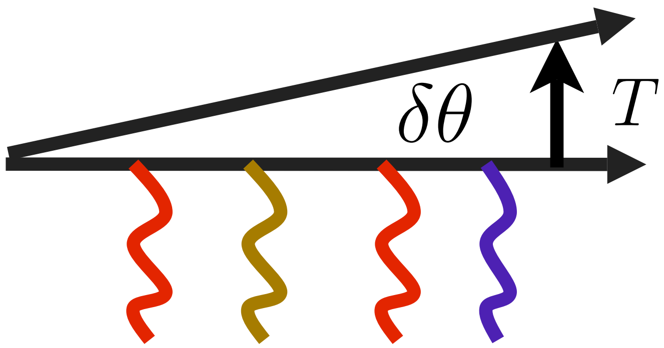
$$\tau_{med} \sim \frac{1}{T}$$

From hydro

$$\tau_{med} \approx 0.5 - 1\,\mathrm{fm}$$

- Energetic/massive probes are produce early prior to the medium formation (E, M>>T). Their production is unchanged by the medium.
- For sufficiently hard processes the production mechanism is under theoretical control.
- The modification of the properties of the probe in nucleus-nucleus collision is a consequence of the interaction with the medium.
- They serve as a diagnostic tool of the medium.

Energy Loss (I)
Massive (slow) Particles



$$\delta\theta = \frac{T}{Mv} \ll 1$$

- Slow velocity in the medium ⇒ radiation can be neglected.
- The energy loss is dominated by collision like processes (collisional energy loss)
- The lost energy is absorbed by the medium.
- The effective description for sufficiently massive particles is Brownian motion.

Heavy Quarks at RHIC

- Heavy Quarks are strongly suppressed and they flow.
- A Langevine model provides an rough description of data.

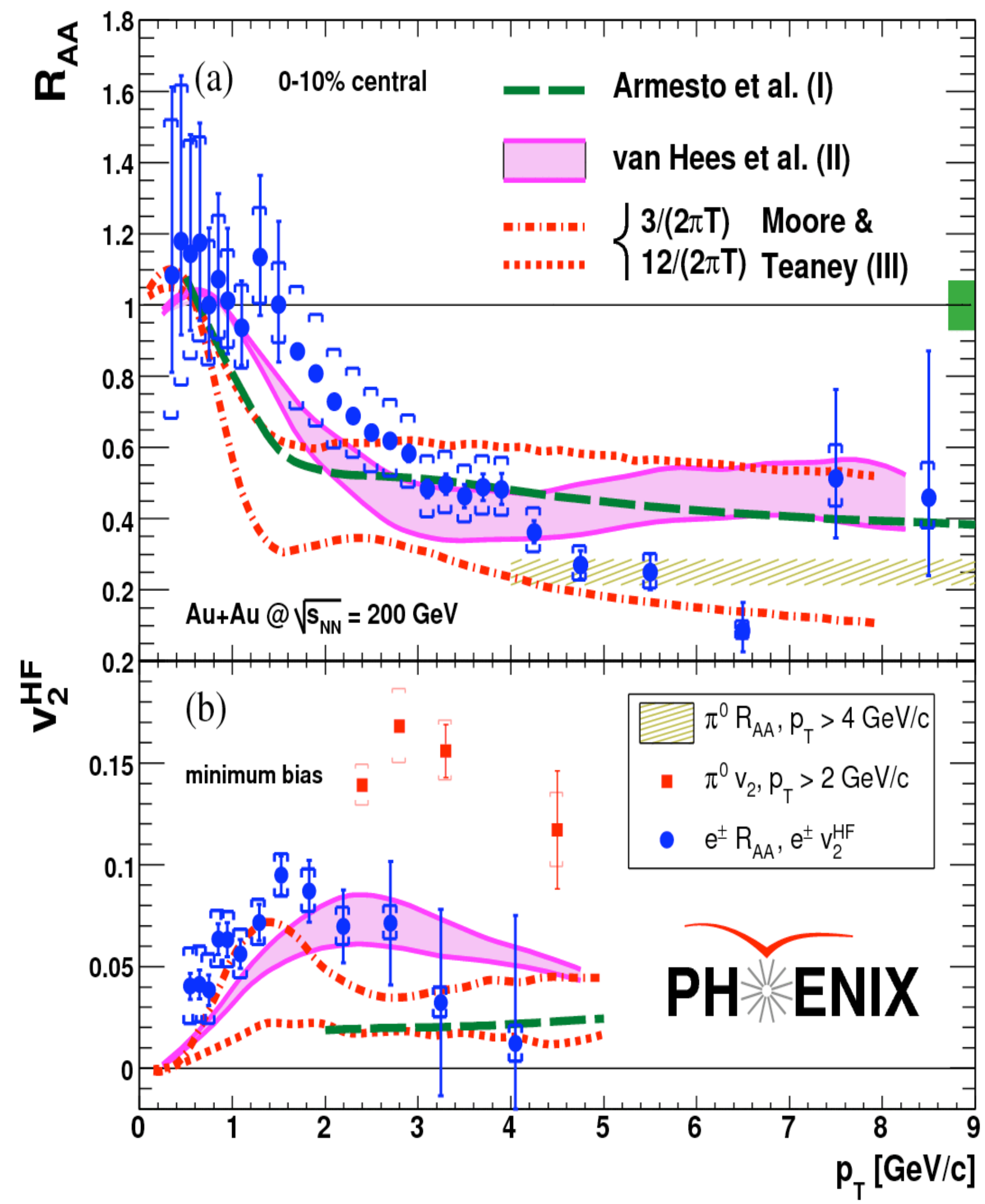
$$\frac{dp}{dt} = -\eta_D p + \xi \qquad \langle \xi(t)\xi(t')\rangle = \kappa\delta(t-t')$$

$$\eta_D = \frac{\kappa}{2MT} \qquad D = \frac{2T^2}{\kappa}$$

- A more involved model involving resonances yields (Hess et al.):

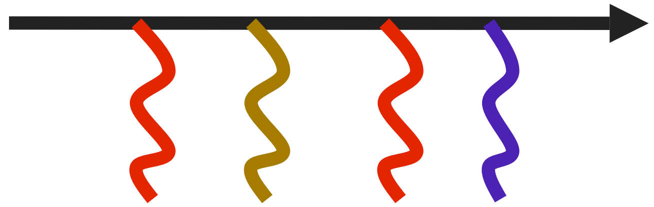
$$D = \frac{3-6}{2\pi T} \qquad \text{(From fit)}$$

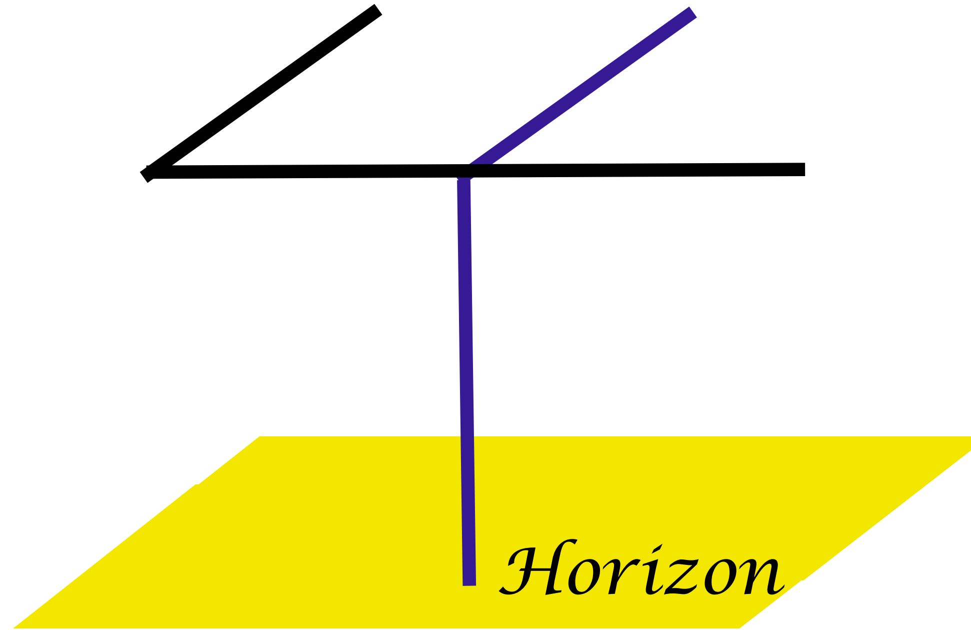
- The diffusion constant is smaller than perturbation theory estimates. $D_{pQCD} \approx \frac{12}{2\pi T}$



HQ at Strong Coupling

$$e^{i\int d\tau u^{\mu} A_{\mu}}$$





- HQ propagation (Wilson line) is given by a classical string stretching down to the horizon.
- At finite velocity the string bends behind the quark end point
- Work must be done against the string tension: there is a flux of momentum from the boundary to the bulk =Energy loss

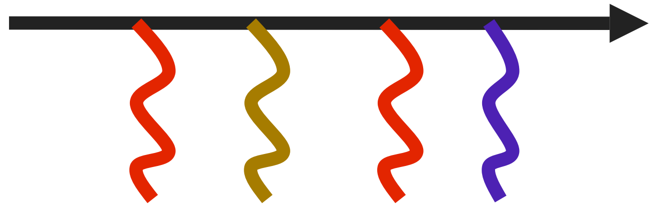
$$\frac{dp}{dt} = -\frac{\pi\sqrt{\lambda}T^2}{2}\gamma v \qquad \left\{ \begin{array}{l} \dfrac{dp}{dt} = -\eta_D p \\ \eta_D = \dfrac{\pi\sqrt{\lambda}T^3}{2MT} \end{array} \right.$$

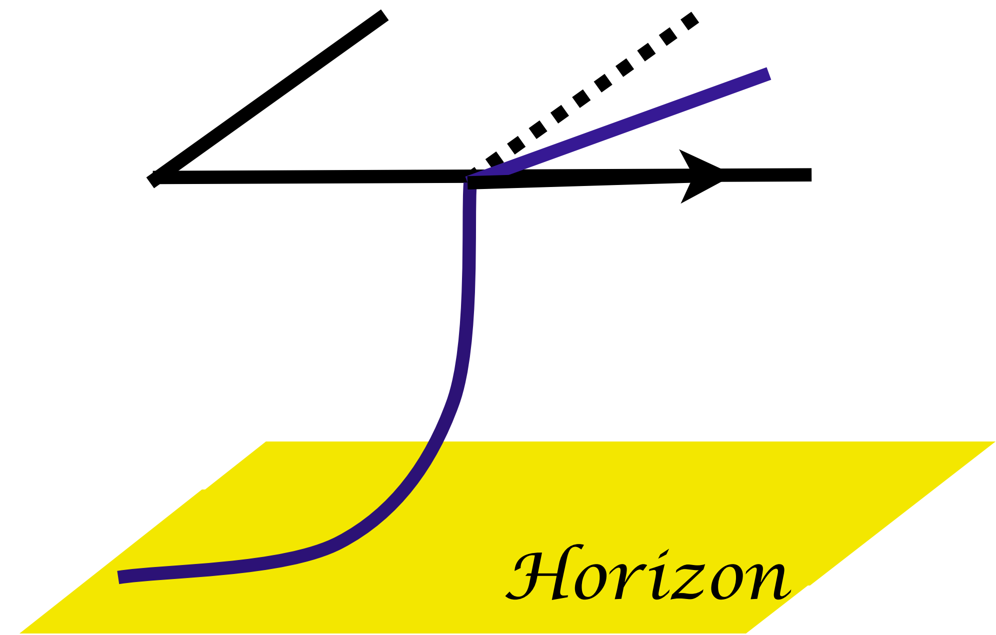
Herzog, Karch, Kovtun, Kozcaz, Yaffe; Gubser

- The drag behavior is valid for ultra relativistic quarks!

HQ at Strong Coupling

$$e^{i\int d\tau u^{\mu}A_{\mu}}$$





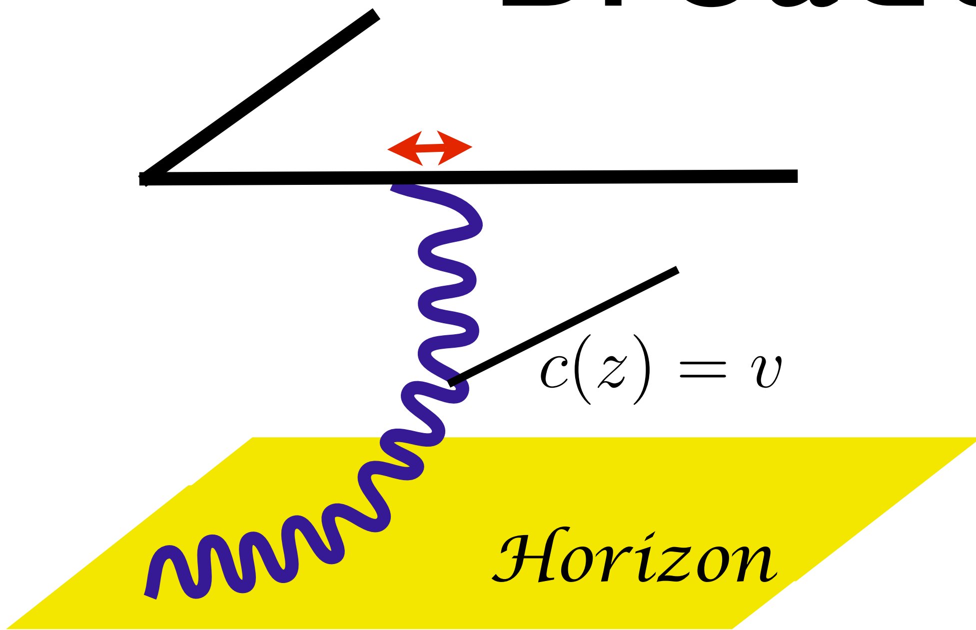
- HQ propagation (Wilson line) is given by a classical string stretching down to the horizon.
- At finite velocity the string bends behind the quark end point
- Work must be done against the string tension: there is a flux of momentum from the boundary to the bulk =Energy loss

$$\frac{dp}{dt} = -\frac{\pi\sqrt{\lambda}T^2}{2}\gamma v \qquad \left\{ \begin{array}{l} \dfrac{dp}{dt} = -\eta_D p \\ \eta_D = \dfrac{\pi\sqrt{\lambda}T^3}{2MT} \end{array} \right.$$

Herzog, Karch, Kovtun, Kozcaz, Yaffe; Gubser

- The drag behavior is valid for ultra relativistic quarks!

Broadening



$$ds^2 = -g_{tt}dt^2 + g_{zz}dz^2$$

$$c(z) = \sqrt{\frac{g_{tt}}{g_{zz}}}$$

- The noise leads to transverse fluctuations of the string. The broadening is obtained from small fluctuations of the string.
- The fluctuations below the scale z=T/√γ are causally disconnected from those above ⇒ world sheet horizon.

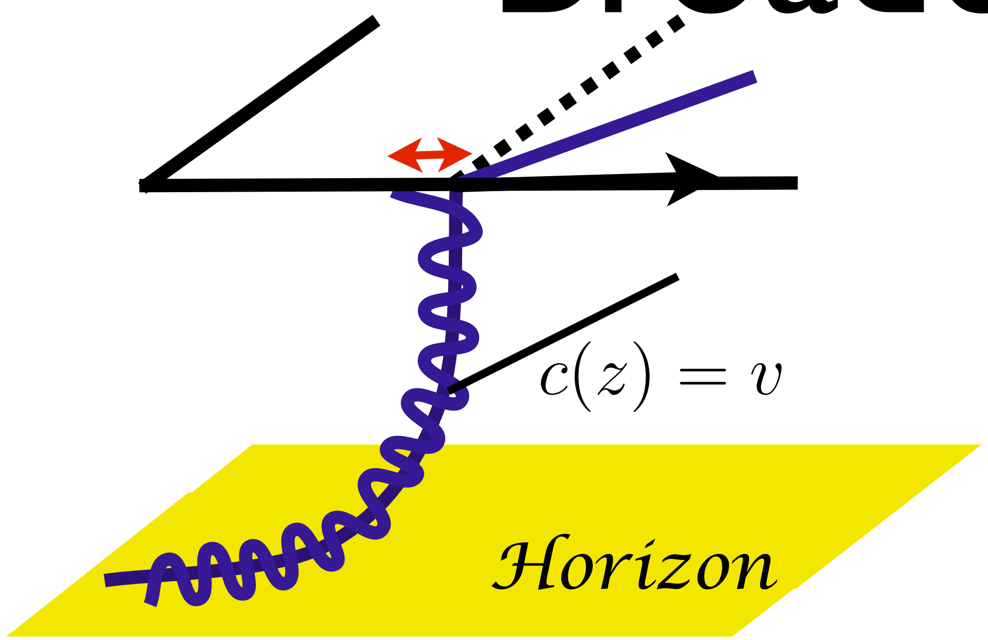
$$\kappa_{L,T} = \frac{2T}{\omega}\mathrm{Im}G_R^{ws}(w) \quad \begin{cases} \kappa_T = \gamma^{1/2}\sqrt{\lambda}\pi T^3 \\ \kappa_L = \gamma^{5/2}\sqrt{\lambda}\pi T^3 \end{cases}$$

JCS, Teaney; Gubser

- At zero velocity it coincides with Langevine prediction.
- There is a strong velocity dependence of the broadening.
- The full Langevine equation can be found by studying the string fluctuations induced by the horizon (Hawking radiation)

Son & Teaney; de Boer, Hubeny; Rangamani, Shigemori; Glecold, Iancu, Mueller

Broadening



$$ds^2 = -g_{tt}dt^2 + g_{zz}dz^2$$

$$c(z) = \sqrt{\frac{g_{tt}}{g_{zz}}}$$

- The noise leads to transverse fluctuations of the string. The broadening is obtained from small fluctuations of the string.
- The fluctuations below the scale z=T/√γ are causally disconnected from those above ⇒ world sheet horizon.

$$\kappa_{L,T} = \frac{2T}{\omega}\mathrm{Im}G_R^{ws}(w) \quad \begin{cases} \kappa_T = \gamma^{1/2}\sqrt{\lambda}\pi T^3 \\ \kappa_L = \gamma^{5/2}\sqrt{\lambda}\pi T^3 \end{cases}$$

JCS, Teaney; Gubser

- At zero velocity it coincides with Langevine prediction.
- There is a strong velocity dependence of the broadening.
- The full Langevine equation can be found by studying the string fluctuations induced by the horizon (Hawking radiation)

Son & Teaney; de Boer, Hubeny; Rangamani, Shigemori; Glecold, Iancu, Mueller

Applications

- The (zero velocity) diffusion constant is small.

$$D_{SYN} = \frac{1}{2\pi T}\left(\frac{1.5}{\alpha_s N_c}\right)^{1/2} \qquad D_{fit} = \frac{3-6}{2\pi T}$$

- The thermalization time of HQ is short

$$t_0 \approx 0.6\,\mathrm{fm}/c\,\frac{m/m_c}{\sqrt{g_{YM}^2 N/10}\,(T/300\,\mathrm{MeV})^2} \qquad t_0 \approx 2\,\mathrm{fm}/c\,\frac{m/m_b}{\sqrt{g_{YM}^2 N/10}\,(T/300\,\mathrm{MeV})^2}$$

Gubser

- The HQ dynamics is dominated by the dynamical scale

$$Q = \sqrt{\gamma} T$$

(Argued to be the saturation scale)

Mueller et al., Iancu

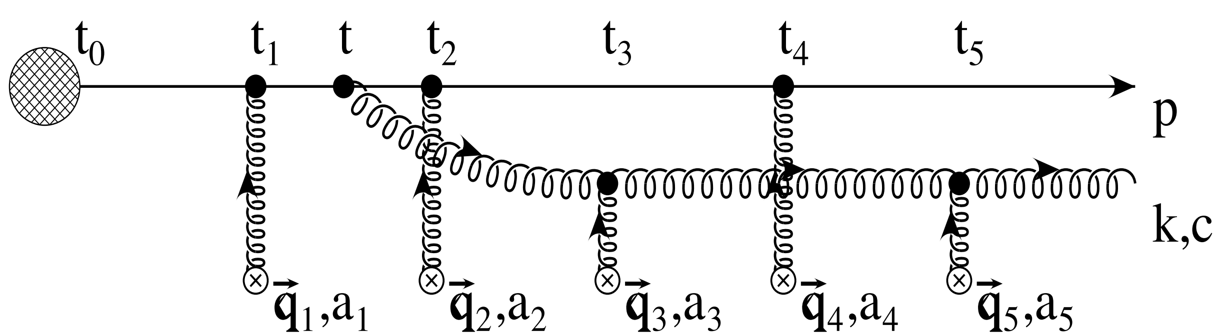
- The HQ feels a lower effective temperature $T_{ws} = T/\sqrt{\gamma}$

JCS, Teaney

- The calculation is not valid for $M_Q < \sqrt{\gamma}\sqrt{\lambda} T$
  - The HQ cannot move faster than the local speed of light.
  - The string action becomes imaginary.
    The strength of the states decays (radiation?)
  - The scale grows with energy ⇒ high energy should be perturbative

Energy Loss (II)
Energetic Particles

BDMPS

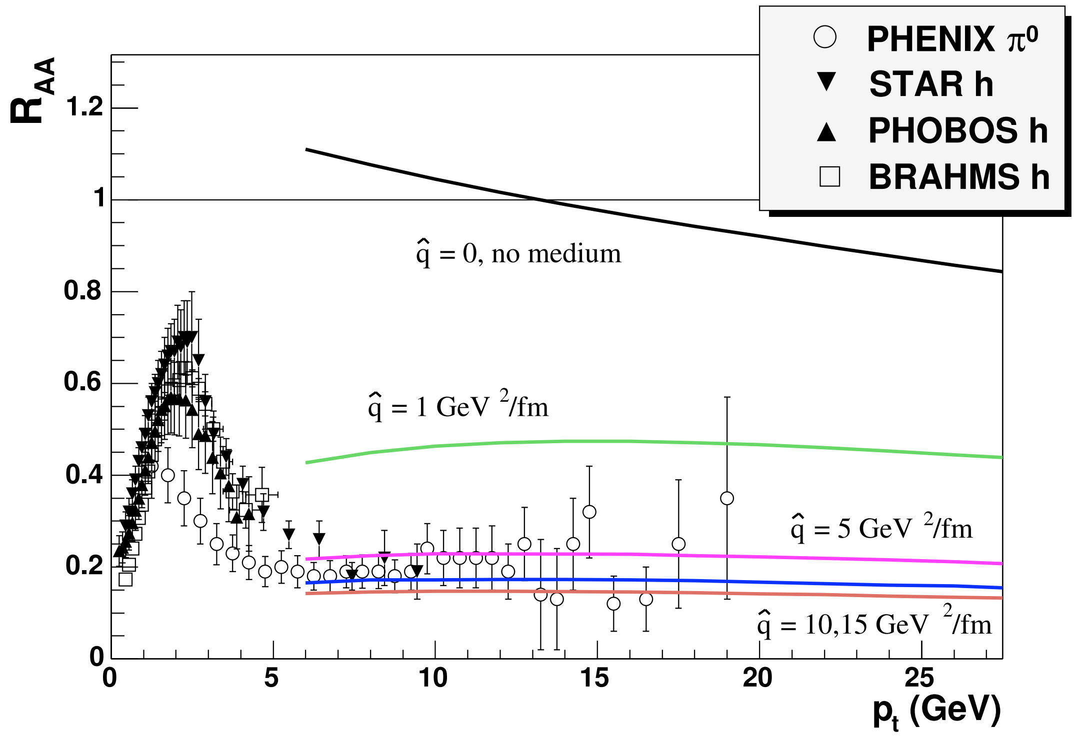


$$\frac{dE}{dx} = \frac{1}{2}\hat{q}L$$

- Dominated by radiation: emission of hard modes (gluons)
- Soft kicks (~T) in the medium lead to hard (k>>T) gluons
- The energy is degraded: not absorbed by the medium
- At high energy the radiation is determined by the re-scattering of the radiated gluon.
- The spectrum is determined by the gluon

$$\hat{q} = \frac{(\text{momentum transferred})^2}{\text{length}} \propto \alpha_s^2 T^3$$

Jet Quenching



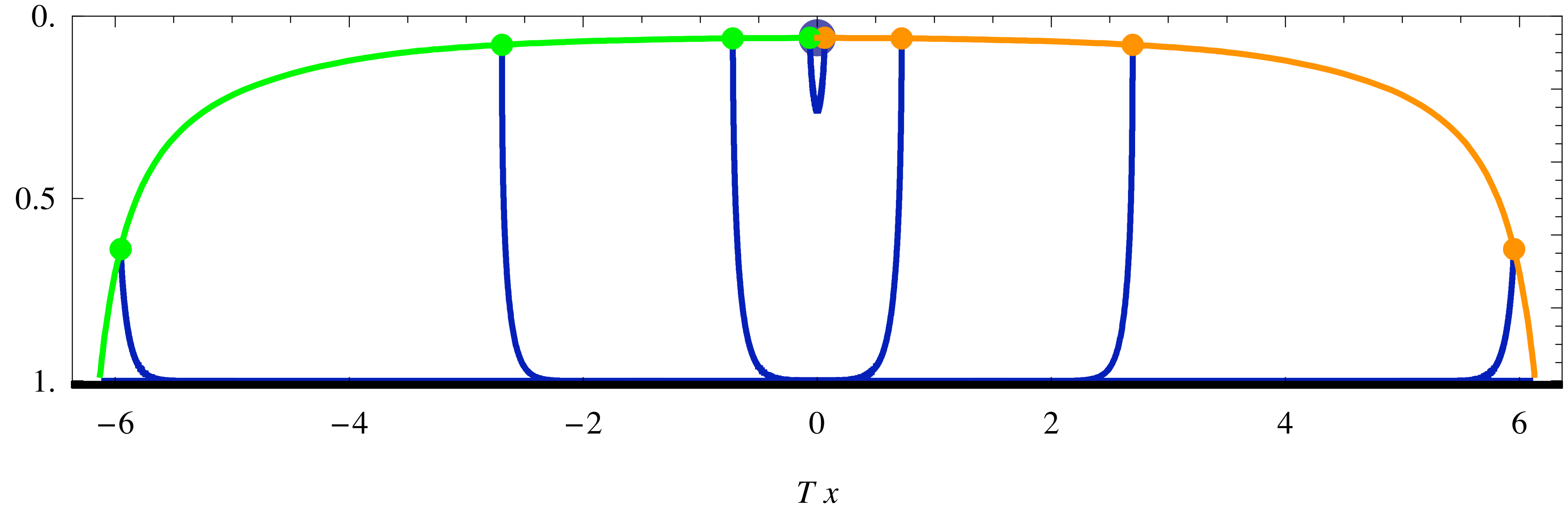
Eskola, Honkanen, Salgado, Wiedemman 05

- The spectrum of hard particles is suppressed with respect to proton proton
- Radiative energy loss describes the suppression (one parameter fit)
- The extracted jet quenching parameter is large.

$$\hat{q}_{fit} \approx 3 - 4 \times \hat{q}_{pQCD} = 10 - 15 \sim \mathrm{GeV}^2/\mathrm{fm}$$

Light Quarks in AdS/CFT

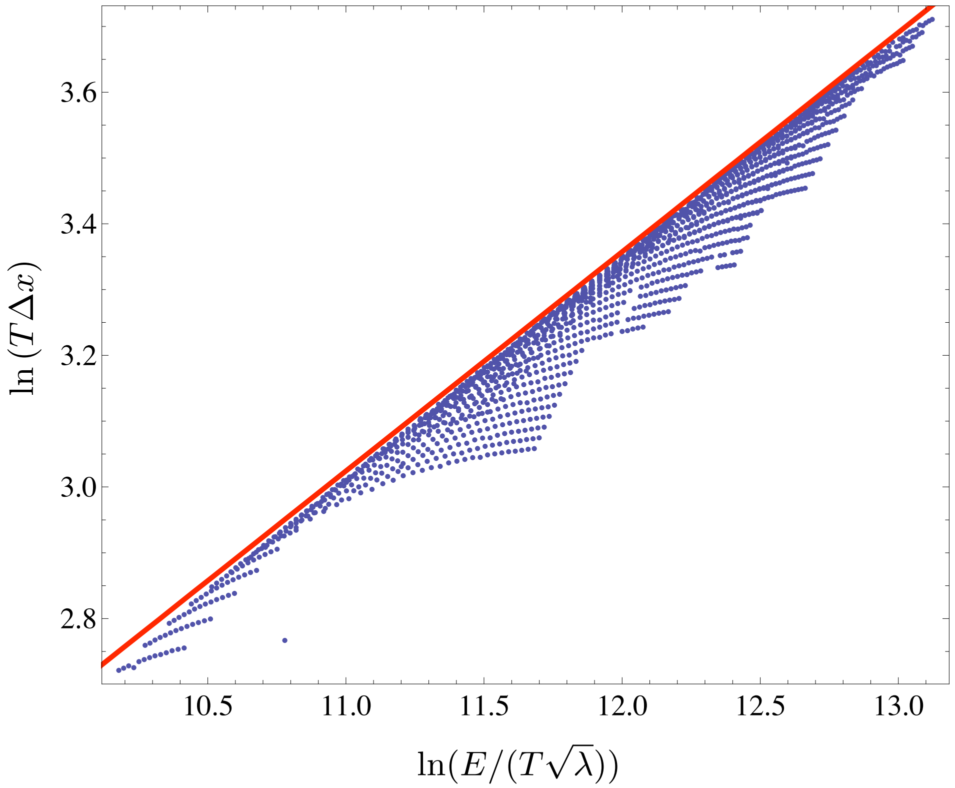
(Chesler, Jensen, Karch, Yaffe)

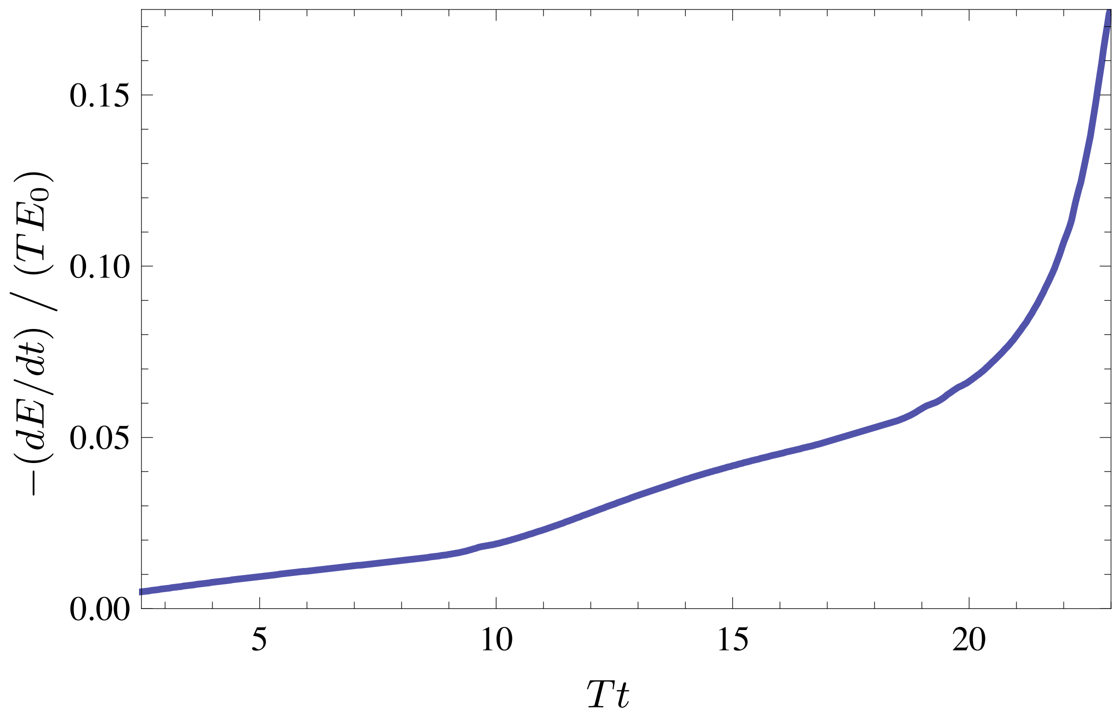


- The string endpoint can fall (no mass scale)
- It follows a light geodesic
- Starting the string at a given height is (qualitatively) related to virtuality of the pair
- When the end point falls in the horizon, the light quark is thermalized.
- The initial profile of the string must be determined, there is freedom in the initial conditions

In Medium Propagation

(Chesler, Jensen, Karch, Yaffe)





- The propagation length depends on the string profile
- There is a maximum distance of propagation

$\Delta x \sim E^{1/3}$ Different from radiative Eloss $\Delta x \sim E^{1/2}$

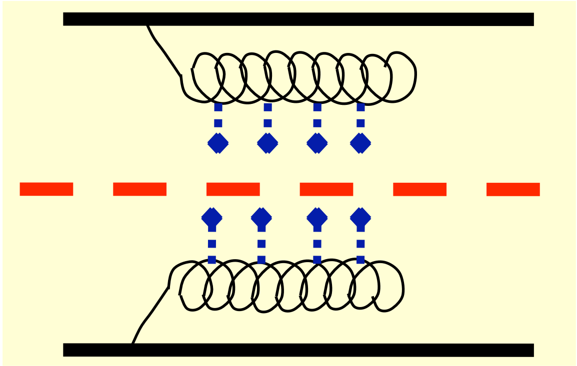
- There is a maximum distance of propagation
- The energy rate is not constant: it is larger at later times.

Caveats

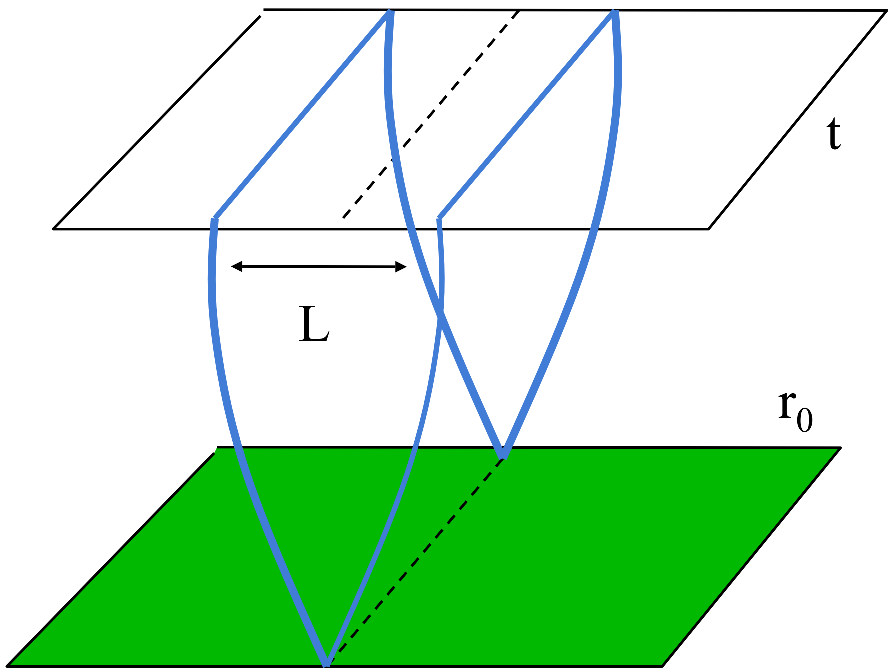
- In N=4 all modes, hard and soft, are strongly coupled
- There are not long lived gluon quasipaticles: there is not radiative loss in this sense
- In QCD the hard gluons are weakly coupled.
- Even if the soft sector is strongly coupled, the parent partons should be able to radiate long lived gluons.
- It is not clear what lessons to take from energetic probes in AdS/CFT
- A "hybrid" approach, even thought less rigorous might be more phenomenologically applicable.

Computing $\hat{q}$ in AdS/CFT

Liu, Rajagopal, Wiedemann



$$W = e^{-\hat{q}L^2\mathcal{T}}$$

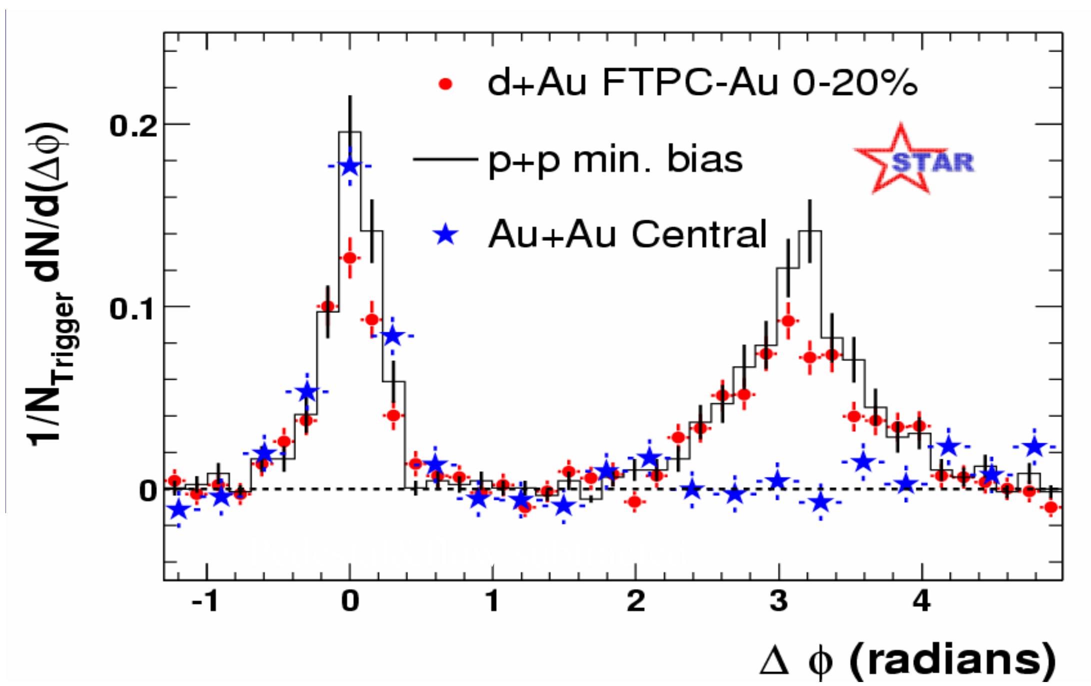


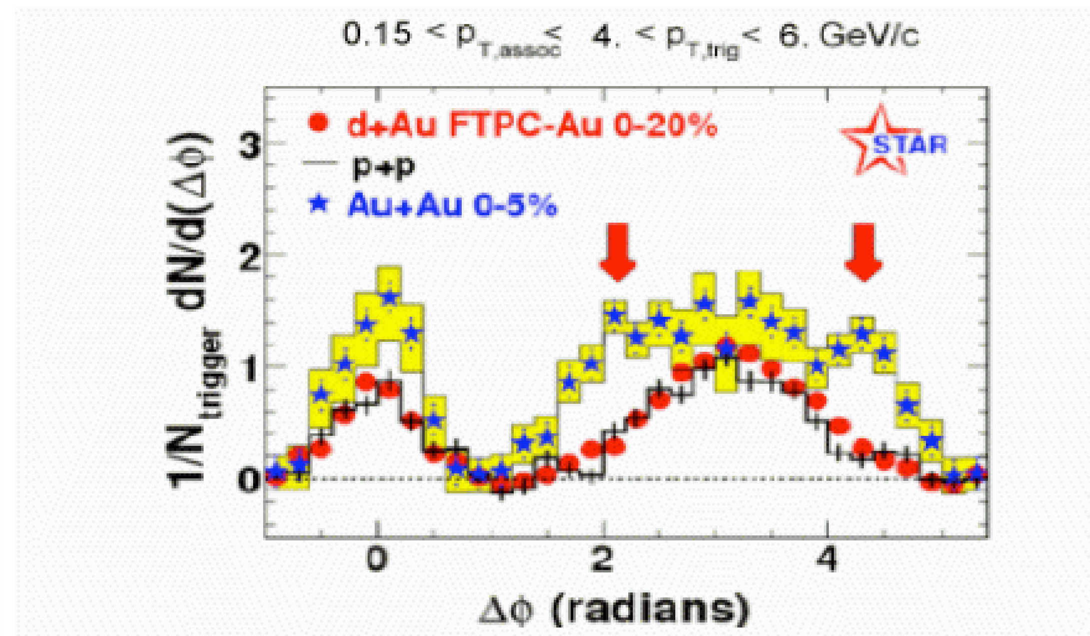
- The (hard) radiative vertex is perturbative
- Gluon spectrum is modified by the in-medium propagation
- This is given by the expectation value of a Wilson line.
- The computation in AdS gives.

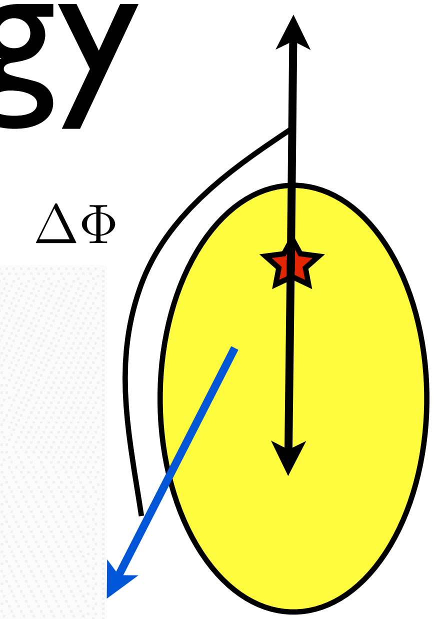
$$\hat{q}_{SYM} = 5.3\sqrt{\lambda}T^3 \underset{\text{(plugging numbers)}}{\Rightarrow} \hat{q}_{QCD} \approx 6 - 12\,\mathrm{GeV}^2/\mathrm{fm}$$

- However:
  It is not clear how to connect with the low momentum
  A description of broadening at all scales is missing

Recovering the lost Energy

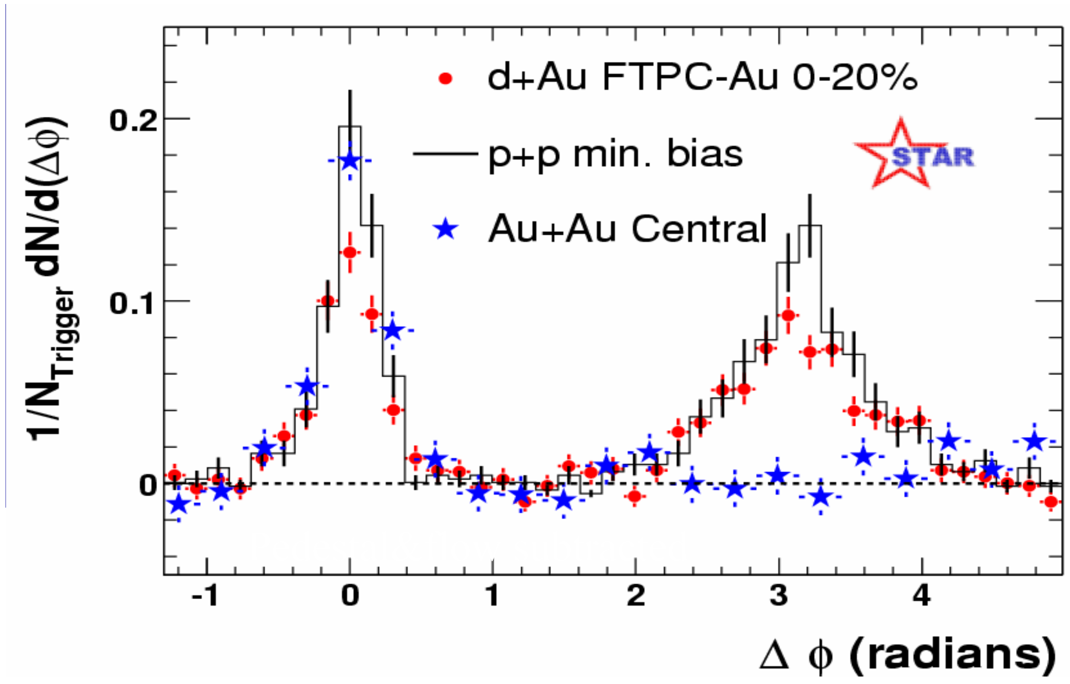


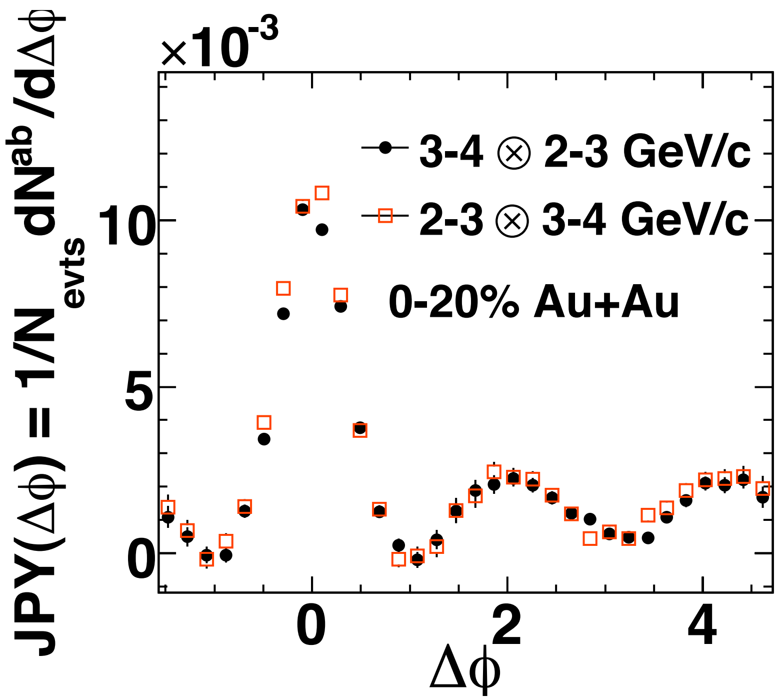


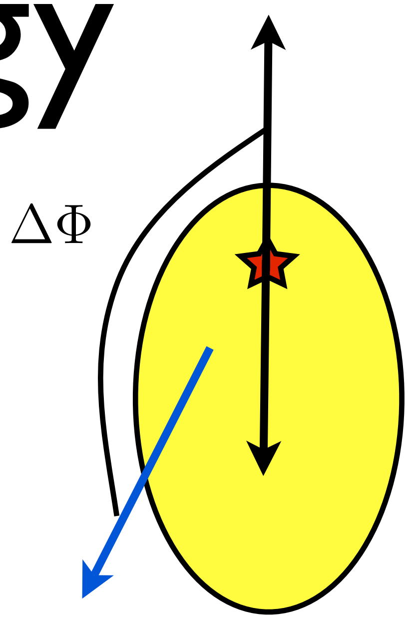


- Associated high momentum hadrons are suppressed.
- There is an enhancement of soft (medium scale) particles.
- The high energy particle modifies the medium (backreaction)
- There is an double peak structure at $\Delta\phi \approx \pi - 1.2$ rad.
- The mean p_T in the double hump is comparable to the medium mean p_T.

Recovering the lost Energy



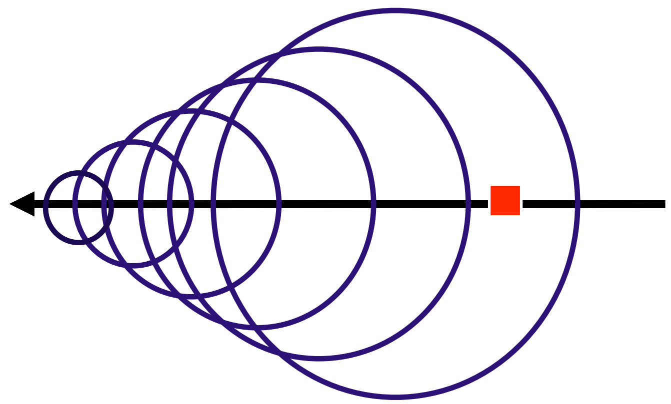


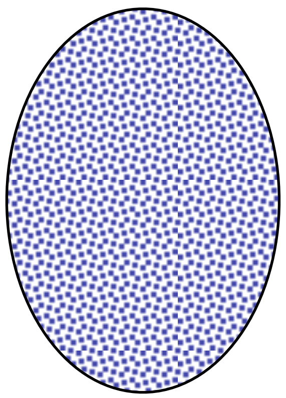


- Associated high momentum hadrons are suppressed.
- There is an enhancement of soft (medium scale) particles.
- The high energy particle modifies the medium (backreaction)
- There is an double peak structure at $\Delta\phi \approx \pi - 1.2$ rad.
- The mean p_T in the double hump is comparable to the medium mean p_T.

Conical Flow

JCS, Shuryak, Teaney;
Stocker; Muller, Rupert
Renk; Neufeld.



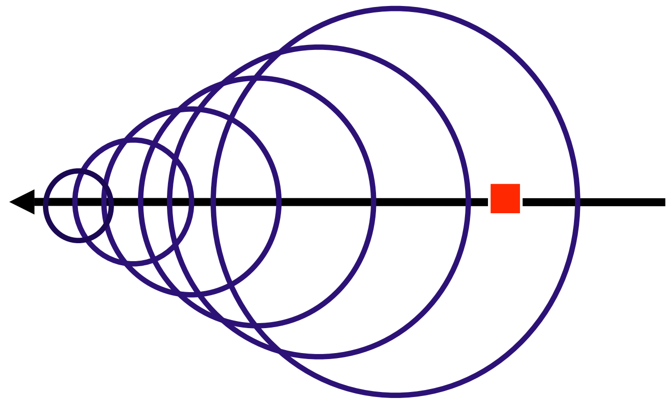


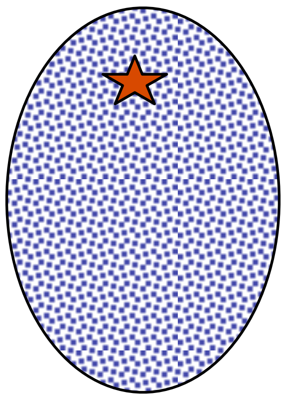
- The medium at RHIC behaves hydrodynamically
- The propagation parton disturbs the medium by depositing energy.
- Partons are supersonic $c_s^2 \leq \frac{1}{3}$
- A mach cone is created moving at the angle $\cos\theta_M = c_s^2$
- This is no the only possible explanation (Cherenkov, large angle radiation, deflected jet...)
- It is not clear wether a point particle can excite hydro modes

Can we find a theory in which this happens?

Conical Flow

JCS, Shuryak, Teaney;
Stocker; Muller, Rupert
Renk; Neufeld.

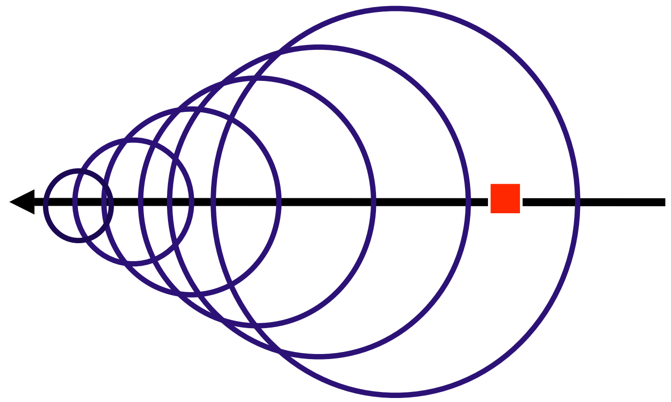


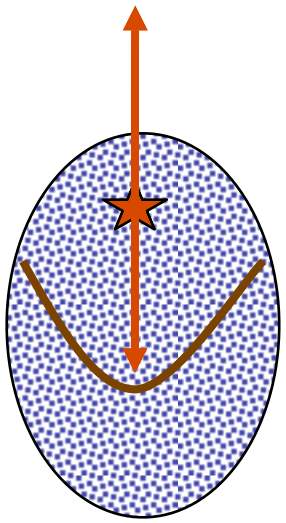


- The medium at RHIC behaves hydrodynamically
- The propagation parton disturbs the medium by depositing energy.
- Partons are supersonic $c_s^2 \leq \frac{1}{3}$
- A mach cone is created moving at the angle $\cos\theta_M = c_s^2$
- This is no the only possible explanation (Cherenkov, large angle radiation, deflected jet...)
- It is not clear wether a point particle can excite hydro modes

Can we find a theory in which this happens?

Conical Flow



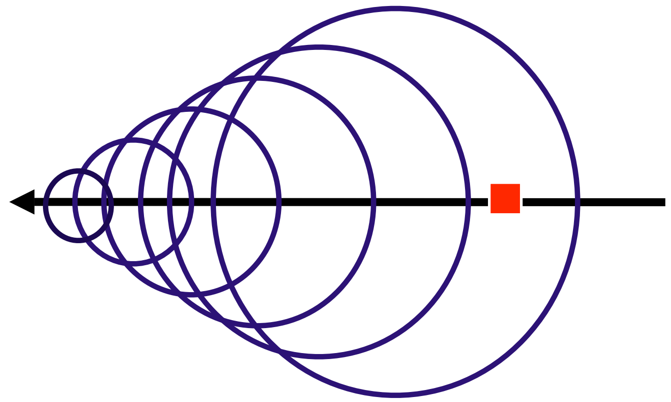


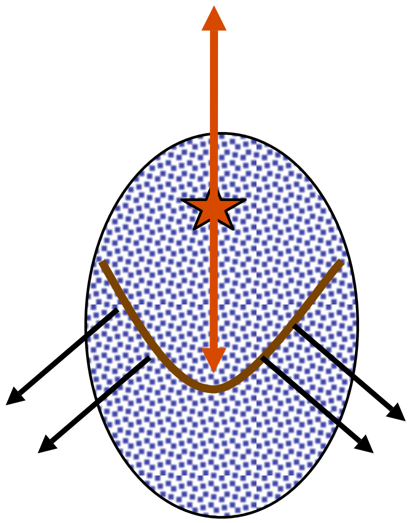
JCS, Shuryak, Teaney; Stocker; Muller, Rupert Renk; Neufeld.

- The medium at RHIC behaves hydrodynamically
- The propagation parton disturbs the medium by depositing energy.
- Partons are supersonic $c_s^2 \leq \frac{1}{3}$
- A mach cone is created moving at the angle $\cos\theta_M = c_s^2$
- This is no the only possible explanation (Cherenkov, large angle radiation, deflected jet...)
- It is not clear wether a point particle can excite hydro modes

Can we find a theory in which this happens?

Conical Flow



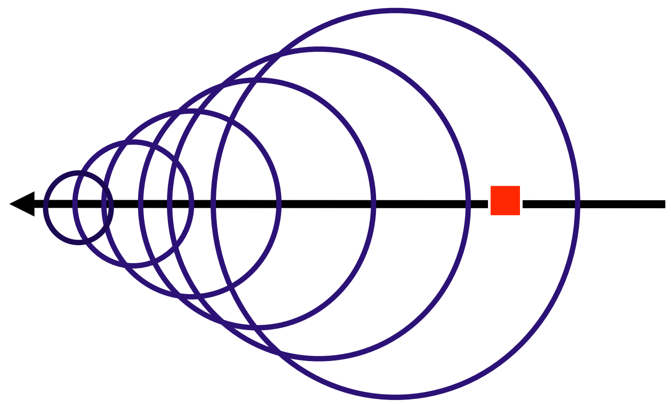


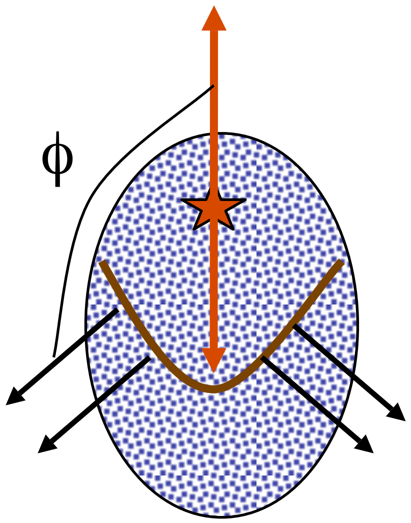
JCS, Shuryak, Teaney; Stocker; Muller, Rupert Renk; Neufeld.

- The medium at RHIC behaves hydrodynamically
- The propagation parton disturbs the medium by depositing energy.
- Partons are supersonic $c_s^2 \leq \frac{1}{3}$
- A mach cone is created moving at the angle $\cos\theta_M = c_s^2$
- This is no the only possible explanation (Cherenkov, large angle radiation, deflected jet...)
- It is not clear wether a point particle can excite hydro modes

Can we find a theory in which this happens?

Conical Flow



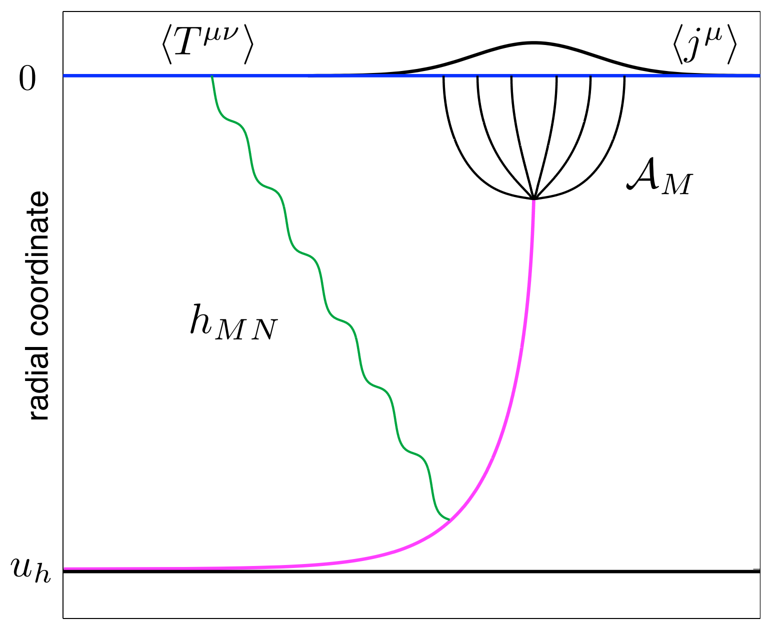


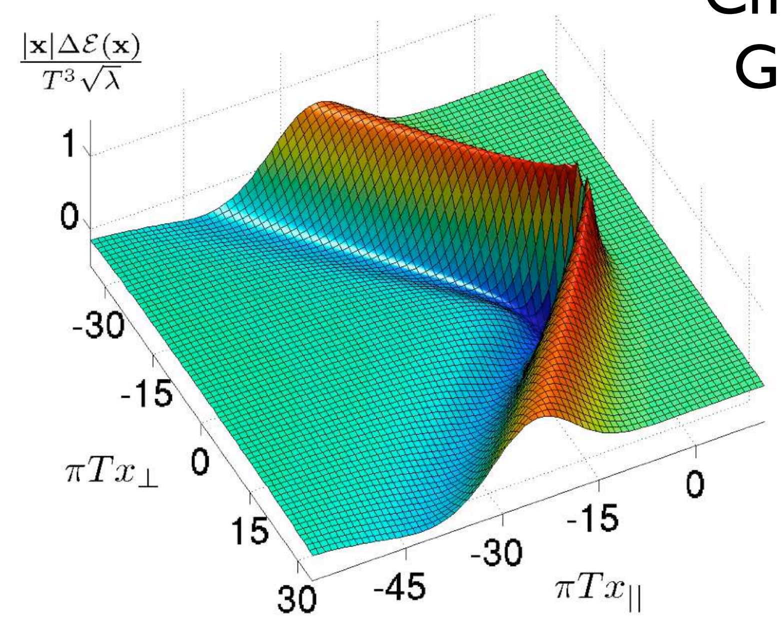
JCS, Shuryak, Teaney;
Stocker; Muller, Rupert
Renk; Neufeld.

- The medium at RHIC behaves hydrodynamically
- The propagation parton disturbs the medium by depositing energy.
- Partons are supersonic $c_s^2 \leq \frac{1}{3}$
- A mach cone is created moving at the angle $\cos\theta_M = c_s^2$
- This is no the only possible explanation (Cherenkov, large angle radiation, deflected jet...)
- It is not clear wether a point particle can excite hydro modes

Can we find a theory in which this happens?

Sound at Strong Coupling



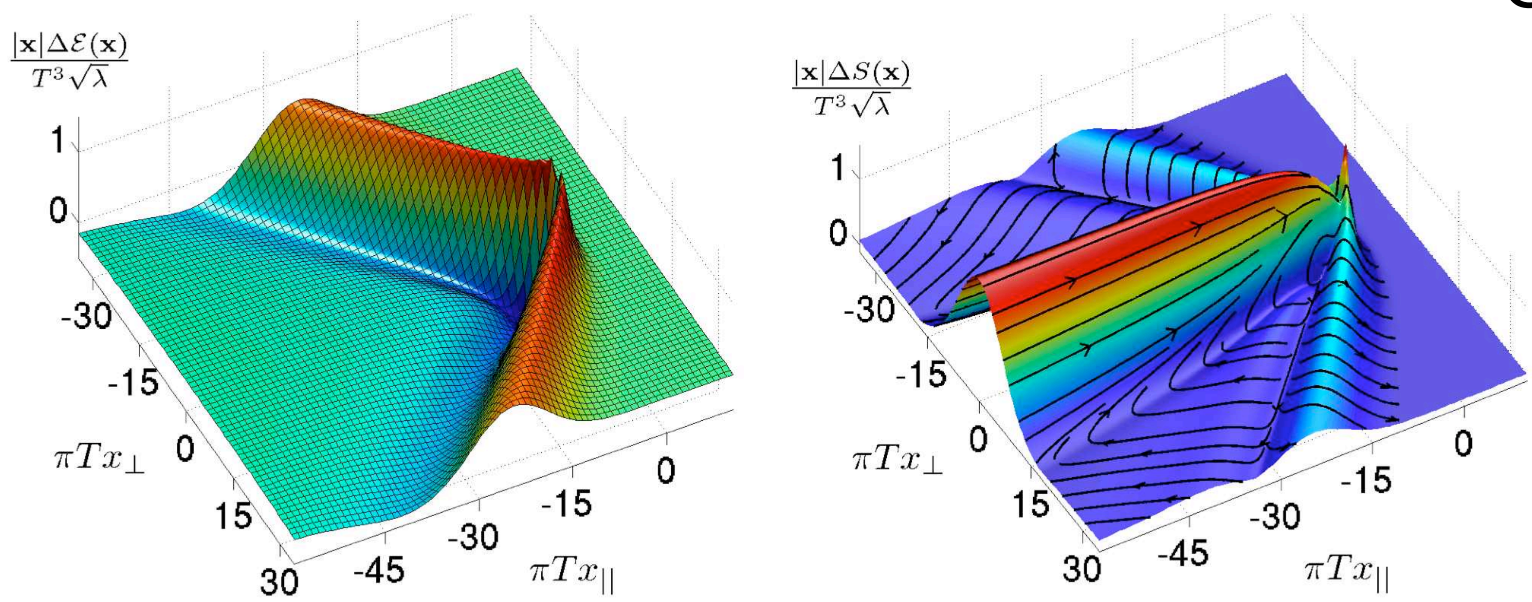


Chesler & Yaffe
Gubser et al
Yarom

- Stress tensor associated to the quark
- Supersonic quarks lead to the formation of Mach cones
- The energy lost by the quark is quickly thermalized
    - Hydrodynamics agrees with the computed fields up to a distance r≈1.5/T.
- Together with Mach cone a large momentum flow along the quark direction is produced.

Sound at Strong Coupling

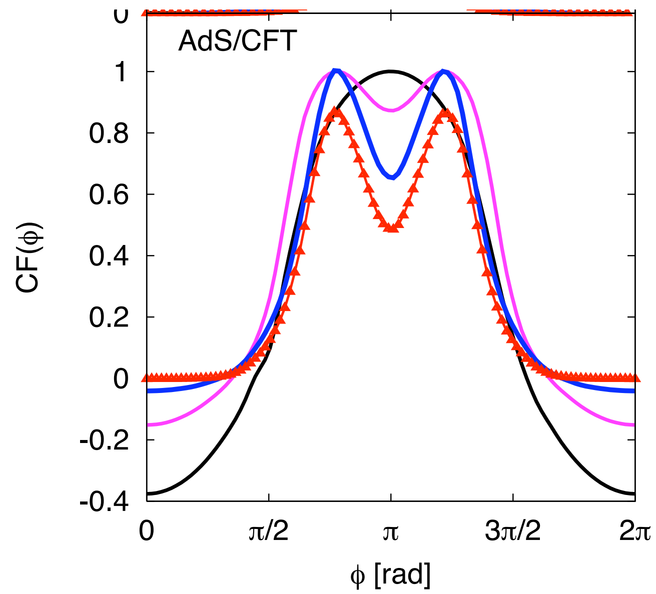
Chesler & Yaffe
Gubser et al
Yarom



- Stress tensor associated to the quark
- Supersonic quarks lead to the formation of Mach cones
- The energy lost by the quark is quickly thermalized
    - Hydrodynamics agrees with the computed fields up to a distance r≈1.5/T.
- Together with Mach cone a large momentum flow along the quark direction is produced.

Hadronization of the fields

(Betz, Gyulassy, Noronha, Torrieri)



- Hydro fields associated to the high energy partons are converted into hadrons
- Cooper-Fry prescription: thermal distribution of particles boosted to the fluid rest frame
- A double peak structure is found

    However it does not reflect the Mach angle

    It is an effect of the near field, no hydrodynamic part.
- Caveats: It is not clear that thermal particle distribution describes the non equilbrated hadronization

    The parton may be absorbed or out of the medium at the hadronization time

Conclusions

- The AdS/CFT correspondence can be used to describe probes in strongly coupled plasmas
- It might be useful to understand those processes dominated by soft exchanges (such as HQ drag)
- It lacks radiation of long lived hard partons: the application to loss of energetic particles is murky.
- At strong coupling, the medium induced disturbance thermalizes quickly.
- This observation reinforces the phenomenological description of hydrodynamical response to particle propagation.