Jet Quenching in Strongly Coupled Plasma

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based on Chesler, KR 1402.6756

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Some Jet Quenching Questions

- How can a jet plowing through strongly coupled quark-gluon plasma lose a decent fraction of its energy and still emerge looking pretty much like an ordinary jet? (In Jorge's talk we will focus on the small differences.)
- Partial answer: if "lost" energy ends up as soft particles with momenta $\sim \pi T$ with directions (almost) uncorrelated with jet direction. Eg more, or hotter, or moving, plasma. Natural expectation in a strongly coupled plasma...
- Still, how do the jets themselves emerge from the strongly coupled plasma looking so similar to vacuum jets?
- Best way to answer this question: a hybrid approach to jet quenching. Treat hard physics with pQCD and energy loss as at strong coupling, see what happens, for example to jet fragmentation functions, and compare to data.
- But, what is dE/dx for a "parton" in the strongly coupled QGP in $\mathcal{N} = 4$ SYM theory? And, while we are at it, what do "jets" in that theory look like when *they* emerge from the strongly coupled plasma of *that* theory?

What happens to 'lost' energy?

- In any strongly coupled approach, energy is 'lost' to hydrodynamic modes with wave vector $<$ or $\lesssim \pi T$.
- The attenuation distance for sound with wave vector q is

$$x_{\text{damping}}^{\text{sound}} = v^{\text{sound}} \frac{1}{q^2} \frac{3Ts}{4\eta}$$

which means that for $q \sim \pi T$ (or $q \sim \pi T/2$) and $v^{\text{sound}} \sim 1/\sqrt{3}$ and $\eta/s \sim 2/4\pi$ we have

$$x_{\text{damping}}^{\text{sound}} \sim \frac{0.3}{T} \left(\text{or} \sim \frac{1.2}{T} \right) .$$

- Energy lost more than a few $x_{\text{damping}}^{\text{sound}}$ before the jet emerges will thermalize, becoming soft particles in random directions. Only energy lost within a few $x_{\text{damping}}^{\text{sound}}$ before the jet emerges will persist as sound waves moving in roughly the same direction as the jet, resulting in a pile of soft particles around the jet. Easier to see in lower T plasma?

Some Jet Quenching Questions

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- **Partial answer: if "lost" energy ends up as soft particles with momenta $\sim \pi T$ with directions (almost) uncorrelated with jet direction. Eg more, or hotter, or moving, plasma. Natural expectation in a strongly coupled plasma...**
- **Still, how do the jets themselves emerge from the strongly coupled plasma looking so similar to vacuum jets?**
- **Best way to answer this question: a hybrid approach to jet quenching. Treat hard physics with pQCD and energy loss as at strong coupling, see what happens, for example to jet fragmentation functions, and compare to data. (Jorge's talk.)**
- **But, what is dE/dx for a "parton" in the strongly coupled QGP in $\mathcal{N} = 4$ SYM theory? And, while we are at it, what do "jets" in that theory look like when *they* emerge from the strongly coupled plasma of *that* theory?**

One More Question

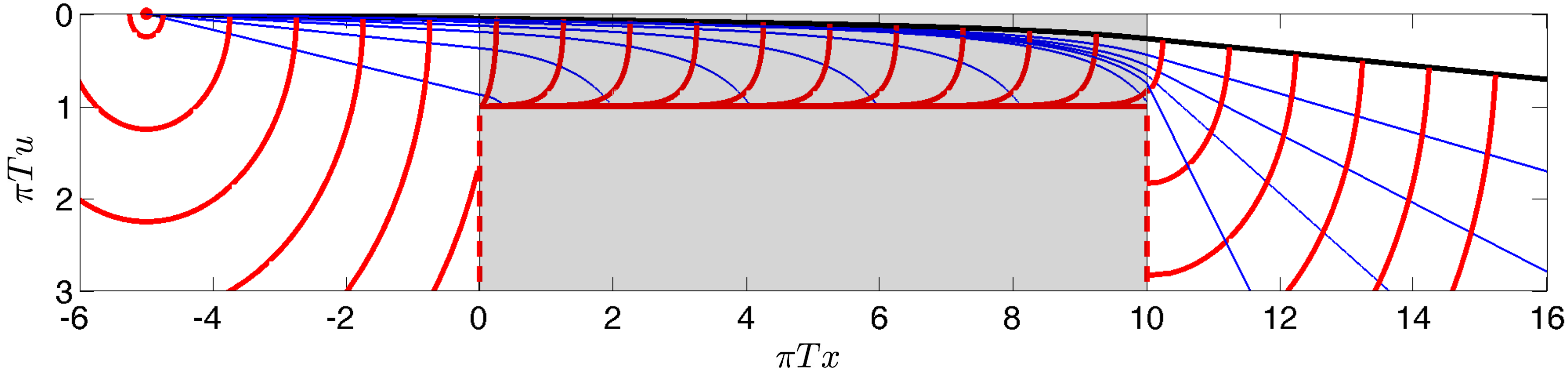
- So, why did I write “jets” instead of jets? Which is to say, what is a jet in $\mathcal{N} = 4$ SYM theory, anyway? There is no one answer, because hard processes in $\mathcal{N} = 4$ SYM theory don’t make jets. Hatta, Iancu, Mueller; Hofman, Maldacena.
- The formation of (two) highly virtual partons (say from a virtual photon) and the hard part of the fragmentation of those partons into jets are all weakly coupled phenomena, well described by pQCD.
- Nevertheless, different theorists have come up with different “jets” in $\mathcal{N} = 4$ SYM theory, namely proxies that share some features of jets in QCD, and have then studied the quenching of these “jets”.
- For example, Chesler, Ho and KR (arXiv:1111.1691) made a collimated gluon beam, and watched it get quenched by the strongly coupled plasma. Qualitative lessons, including about stopping length, but no quantitative calculation of energy loss.

What have we (PC+KR) done?

- We take a highly boosted light quark (Gubser et al; Chesler et al; 2008) and shoot it through a slab of strongly coupled plasma. (G and C et al computed the stopping distance for such "jets" in infinite plasma. Arnold and Vaman did same for differently constructed "jets".)
- We do the AdS/CFT version of the brick problem. (As usual, brick of plasma is not a hydrodynamic solution.)
- Focus on what comes out on the other side of the brick. How much energy does it have? How does the answer to that question change if you increase the thickness of the brick from x to $x + dx$? That's dE/dx.
- Yes, what goes into the brick is a "jet", not a pQCD jet. But, we can nevertheless look carefully at what comes out on the other side of the brick and compare it carefully to the "jet" that went in.
- Along the way, we will get a fully geometric characterization of energy loss. Which is to say a new form of intuition.

Quenching a Light Quark "Jet"

Chesler, Rajagopal, 1402.6756



A light quark "jet", incident with E_{in}, shoots through a slab of strongly coupled $\mathcal{N} = 4$ SYM plasma, temperature T, thickness $L\pi T = 10$, assumed $\gg 1$. What comes out the other side? A "jet" with $E_{\text{out}} \sim 0.64 E_{\text{in}}$; just like a vacuum "jet" with that lower energy, and a broader opening angle.

And, the entire calculation of energy loss is geometric! Energy propagates along the blue curves, which are null geodesics in the bulk. Some of them fall into the horizon; that's energy loss. Some of them make it out the other side. Geometric optics intuition for *why* what comes out on the other side looks the way it does, so similar to what went in.

Quenching a Light Quark "Jet"

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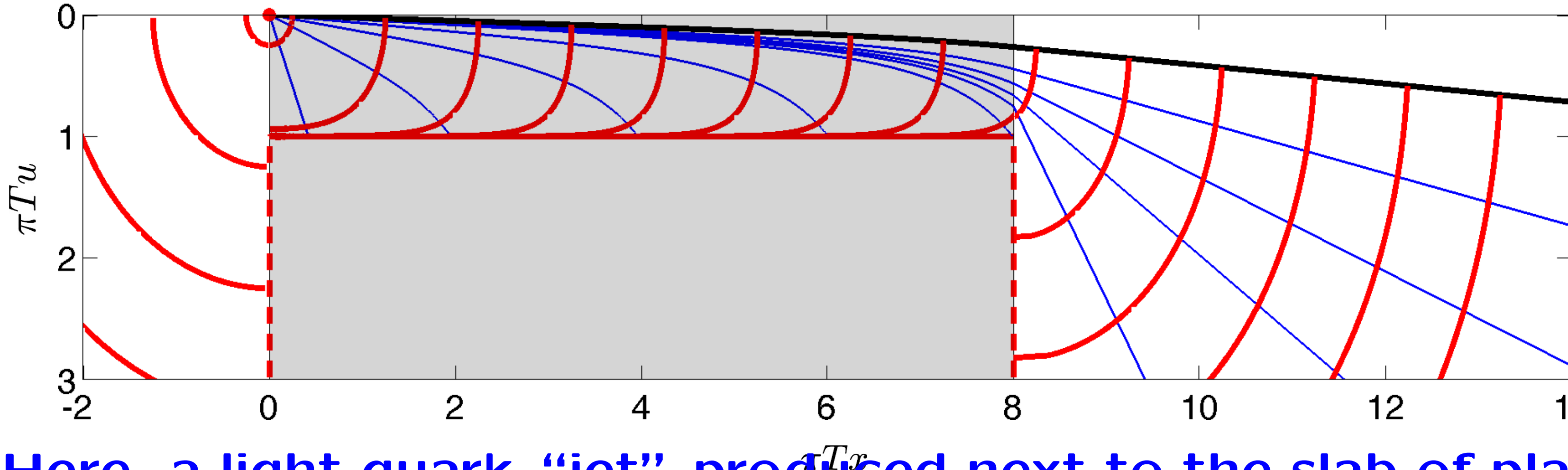

Here, a light quark "jet" produced next to the slab of plasma with incident energy $E_{\text{in}} = 87\sqrt{\lambda}\pi T \sim 87\sqrt{\lambda}$ GeV (modulo a caveat to come) shoots through the slab and emerges with $E_{\text{out}} \sim 66\sqrt{\lambda}$ GeV. Again, the "jet" that emerges looks like a vacuum "jet" with that energy, and broader opening angle.

Geometric understanding of jet quenching is completed via a holographic calculation of the string energy density along a particular blue geodesic, showing it to be $\propto 1/\sqrt{\sigma - \sigma_{\text{endpoint}}}$, with σ the initial downward angle of that geodesic. Immediately implies Bragg peak (maximal energy loss rate as the last energy is lost). Also, opening angle of "jet" $\leftrightarrow$ downward angle of string endpoint.

Quenching a Light Quark "Jet"

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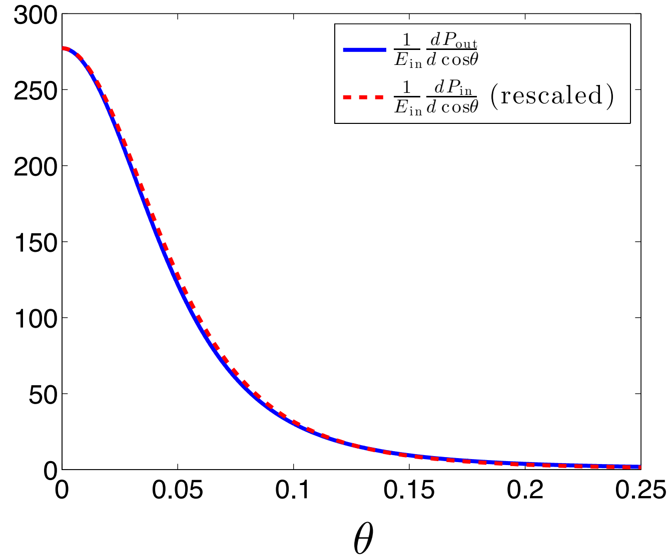

Shape of outgoing "jet" is the same as incoming "jet", except broader in angle and less total energy.

We have computed the energy flow infinitely far downstream from the slab, as a function of the angle θ relative to the "jet" direction.

Quenching a Light Quark "Jet"

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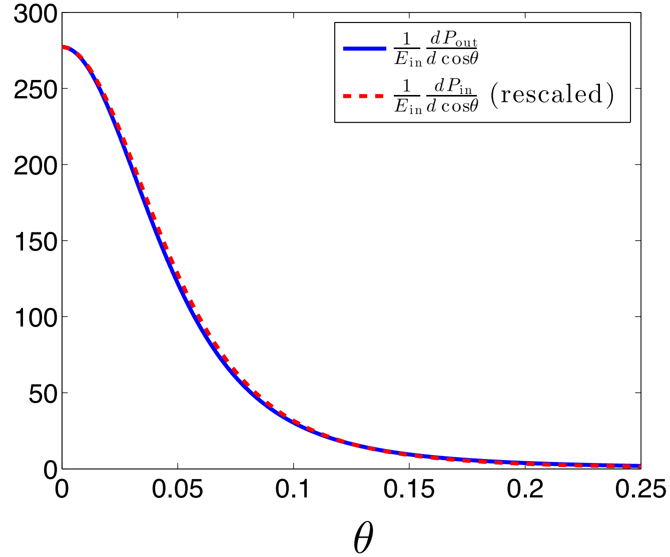

Blue curve is angular shape of the "jet" that emerges from the slab after having been quenched.

Red dashed curve is shape of vacuum "jet", in the absence of any plasma, with θ axis stretched by some factor f (outgoing "jet" is broader in angle) and the vertical axis compressed by more than f^2 (outgoing "jet" has lost energy).

After rescaling, look at how similar the shapes of the incident and quenched "jets" are!

Quenching a Light Quark "Jet"

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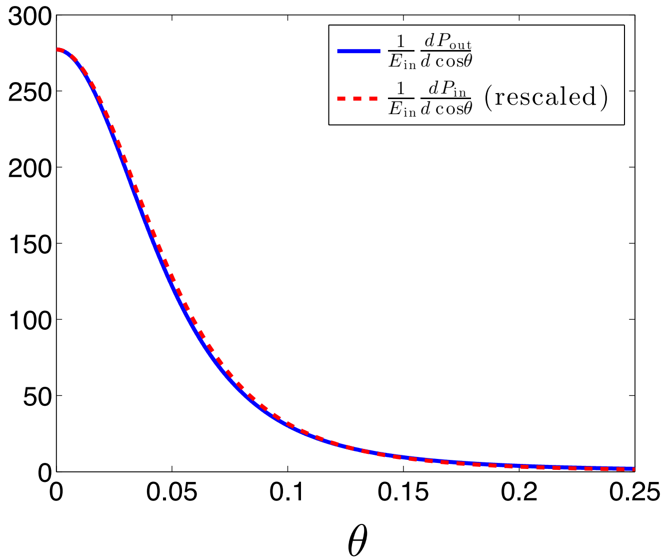
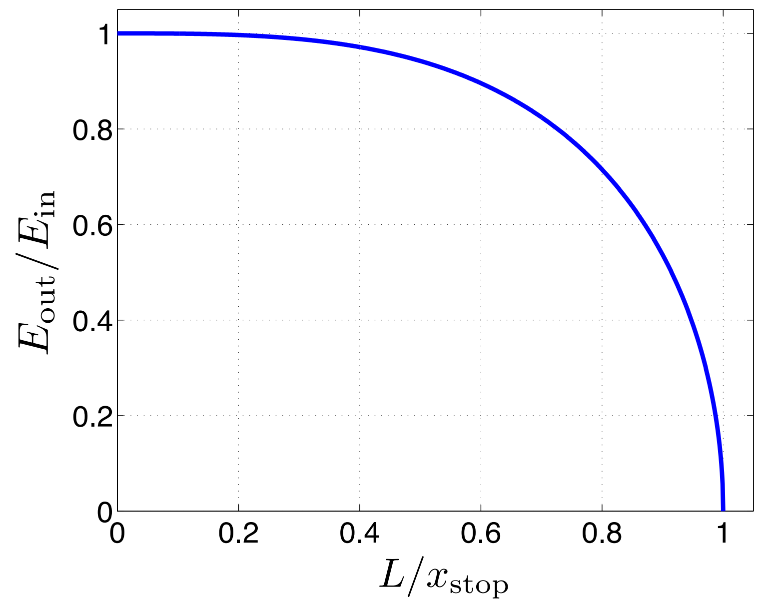




We compute $E_{\rm out}$ analytically, by integrating the power at infinity over angle or by integrating the energy density of the string that emerges from the slab. Geometric derivation of analytic expression for $dE_{\rm out}/dL$, including the Bragg peak:

$$\frac{1}{E_{\rm in}}\frac{dE_{\rm out}}{dL} = -\frac{4L^2}{\pi x_{\rm stop}^2}\frac{1}{\sqrt{x_{\rm stop}^2 - L^2}}$$

where $\pi T x_{\rm stop} \propto (E_{\rm in}/(\sqrt{\lambda}\pi T))^{1/3}$. (Not a power law in L, $E_{\rm in}$, or T; it has a Bragg peak.)

Quenching a Gluon "Jet"

One more necessary input to our hybrid approach: $dE_{\rm out}/dL$ **for a gluon "jet". Use the fact (Gubser et al, 2008) that a gluon "jet" with energy** E **is like** 2 **quark "jets" each with energy** $E/2$**, where both the** 2**'s are the large-**N_c **value of** C_A/C_F**. So, for gluon "jets":**

$$\frac{1}{E_{\rm in}}\frac{dE_{\rm out}}{dL} = -\frac{4L^2}{\pi x_{\rm stop}^2}\frac{1}{\sqrt{x_{\rm stop}^2 - L^2}}$$

where

$$x_{\rm stop}^{\rm gluon} = \left(\frac{C_F}{C_A}\right)^{1/3} \boldsymbol{x}_{\rm stop}^{\rm quark} \ .$$

Note: gluon stopping length is less different from quark stopping length than weak coupling intuition suggests. This has implications for energy loss at LHC relative to that at RHIC.

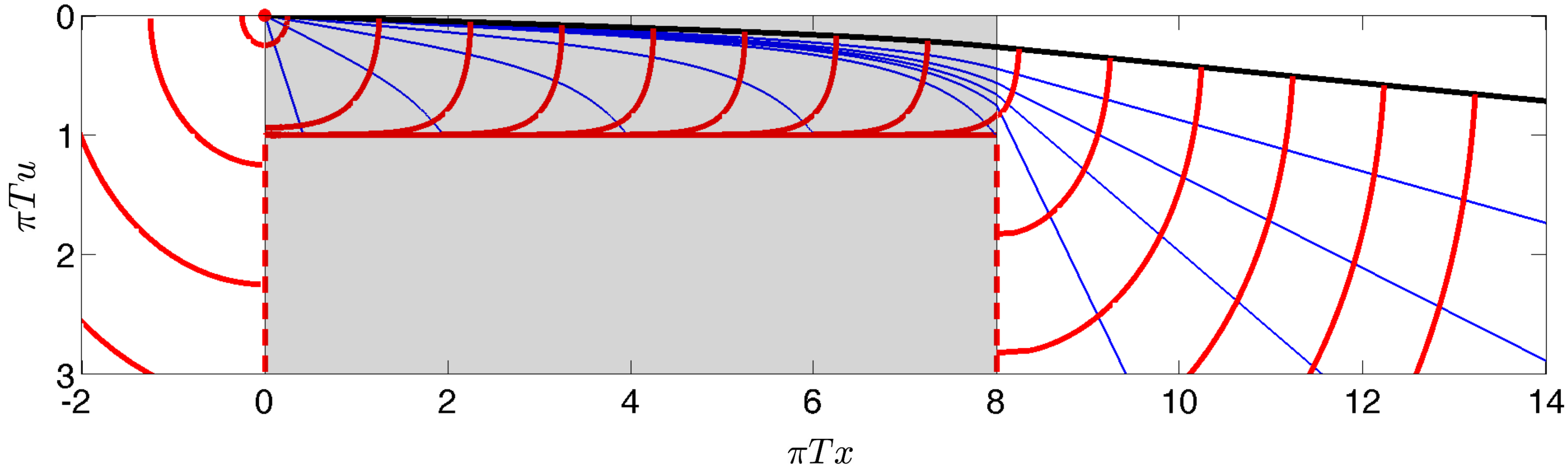
What to do next?

- A hybrid approach in which the dE/dx derived above is applied to every parton in a PYTHIA shower. Using PYTHIA to describe the aspects of jet quenching that should be described by pQCD, but assuming that the energy loss of each QCD parton in the shower is as derived above. $\rightarrow$ Jorge's talk.
- Alternatively, try modelling an entire QCD jet as a "jet" . . .

What to do next?

- Alternatively, try modeling an entire QCD jet as a "jet" . . .
- From this perspective, next priority is analysis of broadening of the "jets".
- How to characterize opening angle of the "jet"? Easiest for us is $\theta_{\text{"jet"}} \equiv m_{\text{"jet"}}/E_{\text{"jet"}} \equiv \sqrt{E^2_{\text{"jet"}} - p^2_{\text{"jet"}}}/E_{\text{"jet"}}$. (But we have the whole profile and so could compare to any jet shape observable.)
- QCD predicts the distribution of m_{in} (e.g. θ_{in}) for each E_{in}. $\mathcal{N} = 4$ SYM does not; each must be specified separately. Send an ensemble of "jets", with a distribution of θ_{in}'s for each E_{in}, for example distributed as in QCD, through the brick of plasma. What comes out the other side? The answer turns out to be surprisingly simple, after you flip the question on its head, after first formulating it in the gravitational dual.

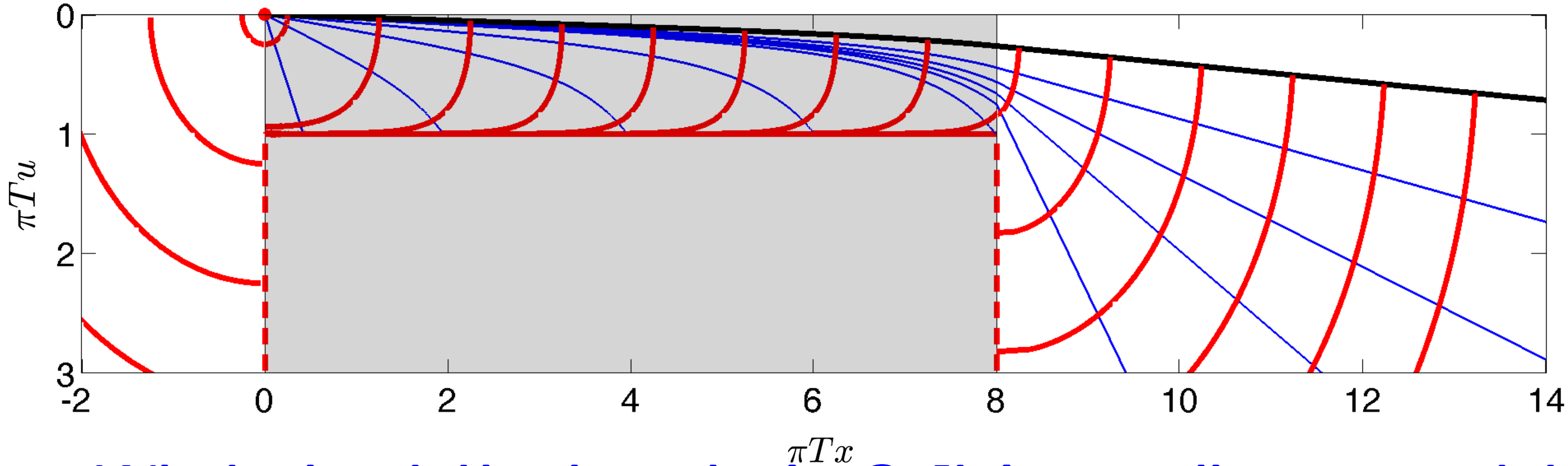
What to do next?



- If there were no plasma, "jet" would have some energy E_{in} and some opening angle $\theta_{\text{in}} \sim \sigma_{\text{in}}$. ($\sigma_{\text{in}}$ is the initial σ of the string endpoint.)
- Due to the slab: $E_{\text{out}} < E_{\text{in}}$, and $\theta_{\text{out}} \sim \sigma_{\text{out}} > \sigma_{\text{in}}$.
- In a sense, everything about the energy loss and the broadening is controlled by $\sigma_{\text{in}} \sim \theta_{\text{in}}$, and the value of E_{in} is, relatively speaking, unimportant.
- Lets start with x_{stop}. It is determined from σ_{in}, as the figure indicates. Explicitly, for small σ_{in} it is given by

$$\pi T\, x_{\text{stop}} = \frac{\Gamma\left(\frac{1}{4}\right)^2}{4\sqrt{\pi}} \frac{1}{\sqrt{\sigma_{\text{in}}}} - 1 + \mathcal{O}\left(\sqrt{\sigma_{\text{in}}}\right) \ .$$

What to do next?



- What about the broadening? It is equally apparent that $\theta_{\text{out}} \sim \sigma_{\text{out}}$ is fully specified by σ_{in} and $\pi T L$.
- What about the energy loss? Rewrite our result as

$$\frac{x_{\text{stop}}}{E_{\text{in}}} \frac{dE_{\text{out}}}{dL} = -\frac{4}{\pi} \frac{L^2}{x_{\text{stop}}^2} \frac{1}{\sqrt{1 - L^2/x_{\text{stop}}^2}}$$

  and see that $E_{\text{out}}/E_{\text{in}}$ is fully specified by L/x_{stop}. And, remember that x_{stop} was fully specified by σ_{in}.
- So, $\sigma_{\text{in}} \sim \theta_{\text{in}}$, the angular size the "jet" would have had if it were in vacuum, tells you how much it broadens and what fraction of its energy it loses.
- Where does E_{in} even enter the gravitational description??

How does E_{in} enter?

- **For a jet with a given σ_{in}, the string energy density is $\propto 1/\sqrt{\sigma - \sigma_{\text{in}}}$. Note the $\propto$. It is in the constant hidden in this $\propto$ that E_{in} enters.**
- **Explicitly, it turns out that**

$$\frac{E_{\text{in}}}{\sqrt{\lambda}\,\pi T} = \frac{\left(\pi T x_{\text{stop}}\right)^3}{\pi^4 \mathcal{C}^3} \propto \frac{1}{\sigma_{\text{in}}^{3/2} \mathcal{C}^3} \,,$$

  where $1/\mathcal{C}^3$ is proportional to the constant hidden in the $\propto$ above.
- **For a given x_{stop}, and remember that means for a given $\sigma_{\text{in}} \propto 1/(\pi T x_{\text{stop}})^2$, you can pick different values of E_{in} by picking different values of $\mathcal{C}$.**
- **Curiously, from the gravitational calculation there is a maximum allowed value of $\mathcal{C}$, which is $\mathcal{C} \approx 0.526$ (Chesler et al; Ficnar, Gubser). This means that for a given σ_{in} there is a minimum allowed E_{in}. If you try to load less energy than that onto the string, the geodesic approximation breaks down.**

What have we learned?

- Send an ensemble of "jets", with a distribution of $\theta_{\rm in}$'s for each $E_{\rm in}$, for example distributed as in QCD, through the brick of plasma. What comes out the other side? We learned to rephrase this...
- Send an ensemble of "jets", with a distribution of $E_{\rm in}$'s for each $\theta_{\rm in}$, for example distributed as in QCD, through the brick of plasma. What comes out the other side?
- All "jets" with the same $\theta_{\rm in}$ that travel through the same path length of plasma will come out with the same $\theta_{\rm out}$. We can make plots of $\theta_{\rm out}$ as a function of $\theta_{\rm in}$ and πTL.
- All "jets" with the same $\theta_{\rm in}$ that travel through the same path length of plasma will come out with the same fractional energy loss $E_{\rm out}/E_{\rm in}$.
- $E_{\rm out}/E_{\rm in}$ is even simpler, since it does not depend separately on $\theta_{\rm in}$ and πTL. It only depends on them via the single combination $L/x_{\rm stop}$.

What to do next?

- It is worth asking whether jet quenching phenomenology in QCD simplifies if one asks about the quenching of jets that would have had a given opening angle in vacuum, rather than about the quenching of jets that would have had a given energy in vacuum, as is conventional.
- The striking, and simple, regularities that we have just learned should make the notion that "jets" can be used to model the quenching of QCD jets easily falsifiable.
- But, doing so is not immediate. In a gamma-jet event, the gamma tells you what the *energy* of the jet would have been in vacuum. How can you know what the opening angle of a jet seen in a PbPb collision would have been, if that jet had been produced in vacuum??
- As far as I can see, although the regularities that we have just seen are striking and simple, comparing them against data will need to be done statistically, on an ensemble basis.
- I remain hopeful that this approach can be falsified.

A Hybrid Weak+Strong Coupling Approach to Jet Quenching

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, arXiv:1405.3864; Jorge's talk

- **Upon fitting one parameter,** *lots* **of data described well, within current error bars. Value of the fitted parameter? $x_{\rm stop}$ is 3 to 4 times longer in QCD plasma than in $\mathcal{N} = 4$ SYM plasma at same T. This is not unreasonable. After all, the two theories have different degrees of freedom. Take all dependences of dE/dx from the strongly coupled calculation, but not the purely numerical factor.**
- **Jet quenching** *looks like* **perturbative fragmentation plus strongly coupled energy loss. Could it** *be* **that?**
- **All this success poses a critical question: if jet quenching observables see the liquid as a liquid, how** *can* **we see the pointlike quasiparticles at short distance scales? This is a prerequisite to understanding** *how* **a strongly coupled liquid can arise in an asymptotically free gauge theory.**

The Jet Quenching Challenge

- **How can we use jets to resolve the short distance structure of the liquid? Jet quenching phenomena involve physics over a range of scales, so jet quenching has long been seen as providing such a microscope. But, how?**

- **In this context, the long list of successful comparisons between jet data and the predictions of the hybrid model that Jorge will describe represent something of a disappointment!**

- **The hybrid is a hybrid of** *weakly coupled vacuum physics* **and** *strongly coupled energy loss + medium physics*. **To the extent that such an approach describes data, that data may be used to learn about the physics of the plasma on length scales at which it is strongly coupled but it cannot tell us about the** *weakly coupled medium physics.*

- **Look for evidence of rare-but-not-too-rare ($1/k_\perp^4$ vs. $\exp[-k_\perp^2]$) hard scattering of partons in a jet off point-like quasiparticles. (D'Eramo, Liu, Rajagopal; Kurkela, Wiedemann)**

Beyond Quasiparticles

- QGP at RHIC & LHC, unitary Fermi "gas", gauge theory plasmas with holographic descriptions are all strongly coupled fluids with no apparent quasiparticles.

- In QGP, with η/s as small as it is, there can be no 'transport peak', meaning no self-consistent description in terms of quark- and gluon-quasiparticles. [Q.p. description self consistent if $\tau_{\rm qp} \sim (5\eta/s)(1/T) \gg 1/T$.]

- Other "fluids" with no quasiparticle description include: the "strange metals" (including high-T_c superconductors above T_c); quantum spin liquids; matter at quantum critical points;... *The* grand challenges at the frontiers of condensed matter physics today.

- Strongly coupled plasma with a holographic description gives us an arena in which we can obtain reliable, qualitative, insights into the behavior of matter in which quasiparticles have disappeared. But, these liquids are liquids on *all* length scales and QGP is not...

The Challenge

- How can we clarify the understanding of fluids without quasiparticles, whose nature is a central mystery in so many areas of science?

- We have one big advantage: our strongly coupled liquid is *not* a liquid if you resolve its structure at short length scales. It is described by an asymptotically free gauge theory. Hence, at short enough length scales it *is* weakly coupled quark and gluon quasiparticles.

- One set of goals for the field is quantifying the properties and dynamics of Liquid QGP at it's natural length scales, where it has no quasiparticles.

- We must also probe, quantify and understand Liquid QGP at *short distance scales*, where it is made of quark and gluon quasiparticles? See *how* the strongly coupled fluid emerges from well-understood quasiparticles at short distances. We need a microscope.

Gauge/String Duality, Hot QCD and Heavy Ion Collisions

Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann

A 460 page book, available from Cambridge University Press.

Intro to heavy ion collisions and to hot QCD, including on the lattice. Intro to string theory and gauge/string duality. Including a 'duality toolkit'.

Holographic calculations that have yielded insights into strongly coupled plasma and heavy ion collisions. Hydrodynamics and transport coefficients. Thermodynamics and susceptibilities. Far-from-equilibrium dynamics and hydrodynamization. Jet quenching. Heavy quarks. Quarkonia. Some calculations done textbook style. In other cases just results. In all cases the focus is on qualitative lessons for heavy ion physics.

From $\mathcal{N} = 4$ SYM to QCD

- **Two theories differ on various axes. But, their plasmas are *much* more similar than their vacua. Neither is supersymmetric. Neither confines or breaks chiral symmetry.**
- **$\mathcal{N} = 4$ SYM is conformal. QCD thermodynamics is reasonably conformal for $2T_c \lesssim T <$?. In model studies, adding the degree of nonconformality seen in QCD thermodynamics to $\mathcal{N} = 4$ SYM has *no* effect on η/s and little effect on observables like those this talk.**
- **The fact that the calculations in $\mathcal{N} = 4$ SYM are done at strong coupling is a feature, not a bug.**
- **Is the fact that the calculations in $\mathcal{N} = 4$ SYM are done at $1/N_c^2 = 0$ rather than $1/9$ a bug??**
- **In QCD thermodynamics, fundamentals are as important as adjoints. No fundamentals in $\mathcal{N} = 4$ SYM, and so far they have only been added as perturbations. This, and $1/N_c^2 = 0$, are in my view the biggest reasons why our goals must at present be limited to qualitative insights.**