Strong Coupling Methods in Jet Quenching

Krishna Rajagopal

MIT

3rd Heavy Ion Jet Workshop

Lisbon, Portugal; June 10, 2014

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a talk in three acts . . .

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Jet Quenching
in Strongly Coupled Plasma

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based upon arXiv:1402.6756, by Paul Chesler and KR

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A Hybrid Weak/Strong Coupling Approach to Jet Quenching

Dani Pablos

Universitat de Barcelona

based upon arXiv:1405.3864,

by Jorge, Doga, Gui, Dani and KR

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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?**
- **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. That is what Dani Pablos will do in the second 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?**

What happens to 'lost' energy?

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

$$x^{\rm sound}_{\rm damping} = v^{\rm sound}\frac{1}{q^2}\frac{3Ts}{4\eta}$$

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

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

- Energy lost more than a few $x^{\rm sound}_{\rm damping}$ before the jet emerges will thermalize, becoming soft particles in random directions. Only energy lost within a few $x^{\rm sound}_{\rm damping}$ 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?

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One More Question

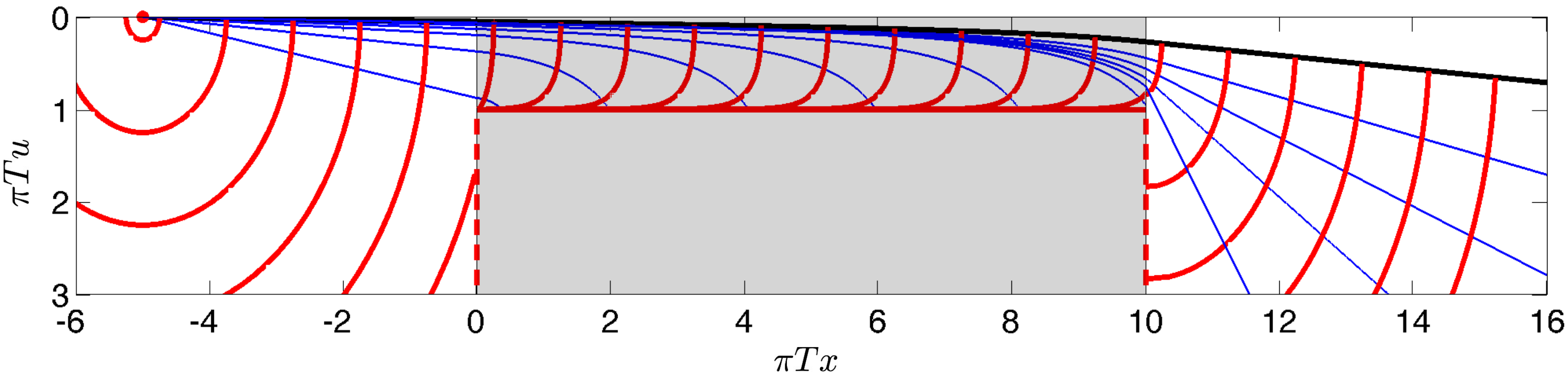
- **So, why did I write "jets" instead of jets? Which is to say, what is a jet in $\mathcal{N} = 4$ SYM theory, anyway? There is no one answer, because hard processes in $\mathcal{N} = 4$ SYM theory don't make jets.** Hatta, Iancu, Mueller; Hofman, Maldacena.
- **The formation of (two) highly virtual 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

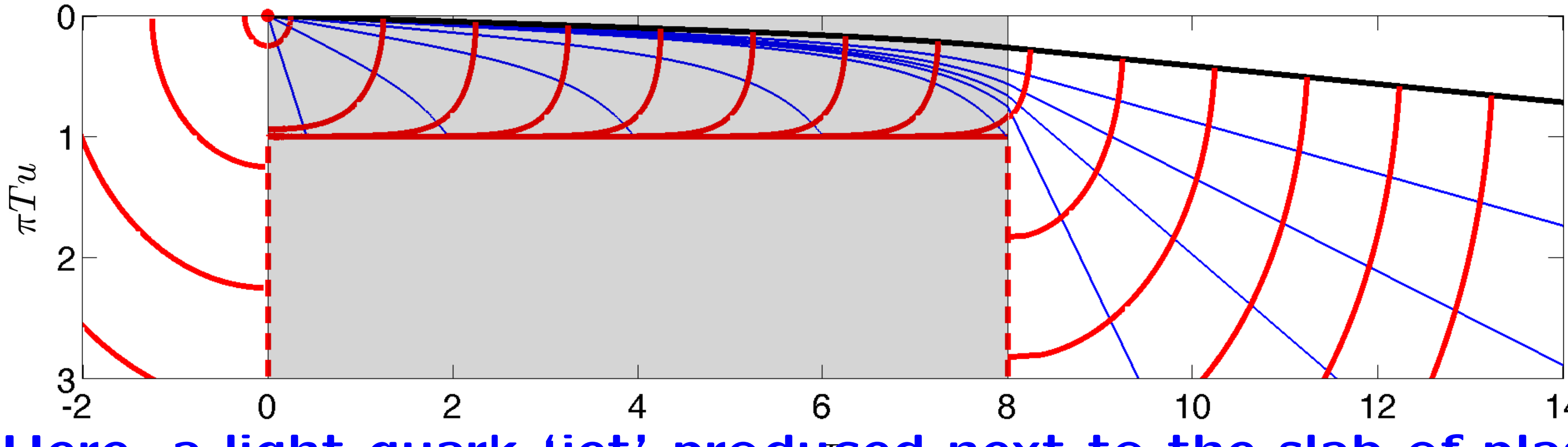


A light quark “jet”, incident with $E_{\rm in}$, shoots through a slab of strongly coupled $\mathcal{N} = 4$ SYM plasma, temperature T, thickness $L\pi T = 10$, assumed $\gg 1$. What comes out the other side? A “jet” with $E_{\rm out} \sim 0.64 E_{\rm in}$; just like a vacuum “jet” with that lower energy,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

Chesler, Rajagopal, 1402.6756



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 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.

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.

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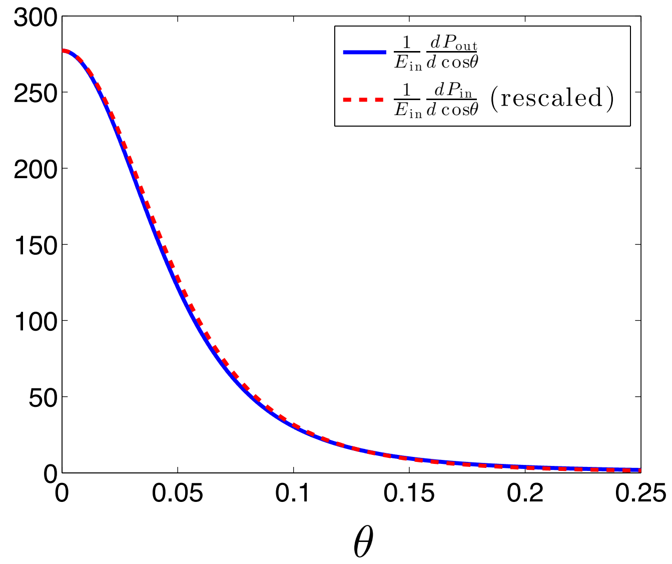
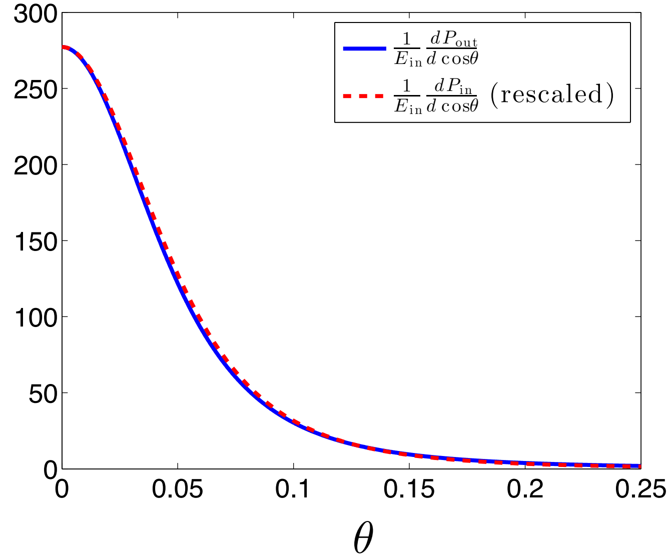


Shape of outgoing “jet” is the same as incoming “jet”, except broader in angle and less total energy.

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"

Chesler, Rajagopal, 1402.6756



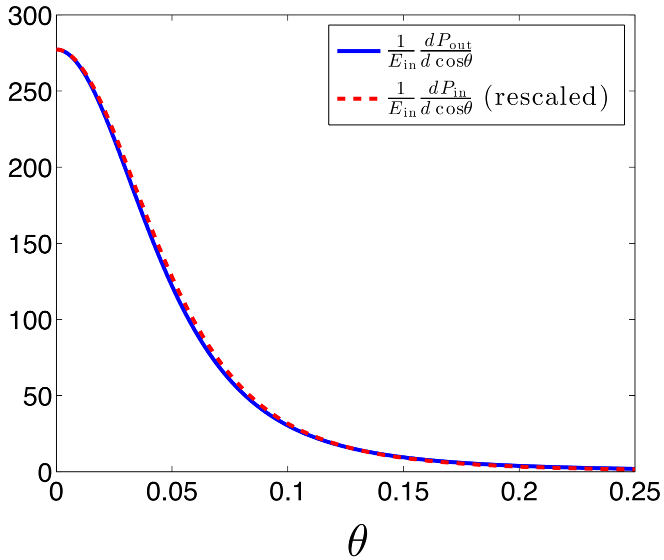
Blue curve is angular shape of the "jet" that emerges from the slab after having been quenched.

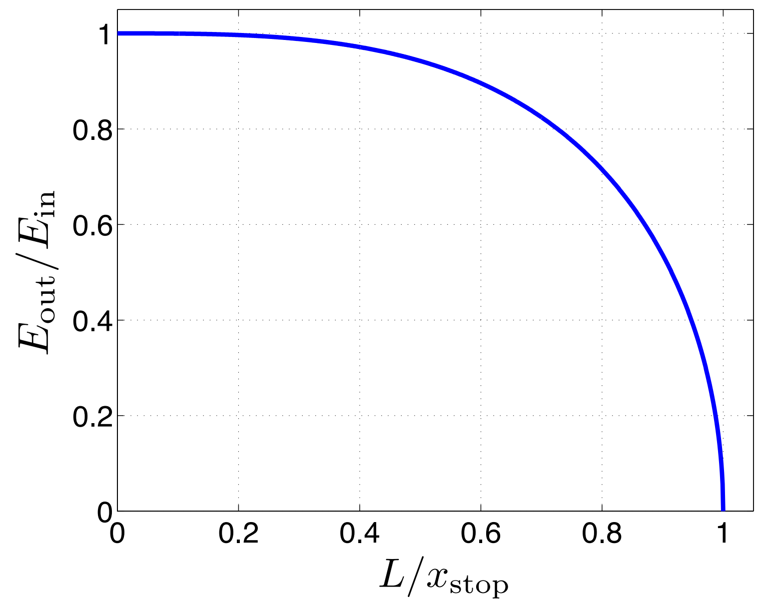
Red dashed curve is shape of vacuum "jet", in the absence of any plasma, with θ axis stretched by some factor f (outgoing "jet" is broader in angle) and the vertical axis compressed by more than f^2 (outgoing "jet" has lost energy).

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

Quenching a Light Quark "Jet"

Chesler, Rajagopal, 1402.6756





We compute E_{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_{out}/dL, including the Bragg peak:

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

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

Quenching a Light Quark "Jet"

One more thing Dani needs is $dE_{\rm out}/dL$ for a gluon "jet". Use the fact (Chesler 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

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

We give this to Dani also. (Note: gluon stopping length is much less different from quark stopping length than weak coupling intuition would suggest. This has implications for energy loss at LHC relative to that at RHIC.)

What to do next?

- Dani's talk. He will present 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.
- Alternatively, try modelling an entire QCD jet as a "jet"...
- From this perspective, next priority is quantitative analysis of broadening of the "jets".

What to do next?

- **How best to characterize the opening angle of the "jet"? Maybe $\theta_{\rm jet} \equiv m_{\rm jet}/E_{\rm jet} \equiv \sqrt{E_{\rm jet}^2 - p_{\rm jet}^2}/E_{\rm jet}$? Easy for us to calculate. But, are there better definitions of $\theta_{\rm jet}$, given that we have the whole profile?**
- **QCD predicts the distribution of $m_{\rm in}$ (eg $\theta_{\rm in}$) for each $E_{\rm in}$. $\mathcal{N} = 4$ SYM does not; each must be specified separately. Send an ensemble of "jets", with $\theta_{\rm in}$ for each $E_{\rm in}$ distributed as in QCD, through the brick of plasma. For each "jet", $E_{\rm out} < E_{\rm in}$ and $m_{\rm out} > m_{\rm in}$. Analyze distribution of $m_{\rm out}$ (eg $\theta_{\rm out}$) for a given $E_{\rm out}$. How similar is the distribution of $m_{\rm out}$ for "jets" with a given $E_{\rm out}$ to the distribution of $m_{\rm in}$ for incident "jets" with energy $E_{\rm out}$?**
- **Can experimentalists measure change in shape of jets in PbPb collisions relative to shape of jets with the same** *initial* **energy in pp collisions?**

What to do next?

- Can we tailor the energy density along the dual string by hand so as to design the angular shape of the "jets" to match the angular shape of QCD jets?
- Redo the present analysis for a hydrodynamic solution rather than for a brick.
- It is important to pursue these investigations of "jet" quenching that assume that *all* the physics is strongly coupled, to see where they lead. But, as I said at the beginning, data seem to demand a hybrid approach ...

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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.**

The Jet Quenching Challenge

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

- **In this context, the long list of successful comparisons between jet data and the predictions of the hybrid model that Dani described represent quite a disappointment!**

- **Dani described 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.*

- **The most interesting uses of a hybrid model** *of the type that Dani presented* **could in the end be the study of where it fails. (More sophisticated hybrids could be developed.)**

A Hybrid Weak+Strong Coupling Approach to Jet Quenching

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, arXiv:1405.3864

- **Upon fitting one parameter, *lots* of data described well, within current error bars. Value of the fitted parameter? x_{stop} is three to four times longer in QCD plasma than in $\mathcal{N} = 4$ SYM plasma. This is not unreasonable. We are taking all dependences of dE/dx from the strongly coupled calculation, but not the purely numerical factor: after all, the two theories have different degrees of freedom.**
- **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?**
- **Successfully describing jet quenching data using fragmentation as in vacuum plus strongly coupled energy loss and strongly coupled physics of the medium is in this sense a disappointment!**

A Hybrid Weak+Strong Coupling Approach to Jet Quenching

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, arXiv:1405.3864

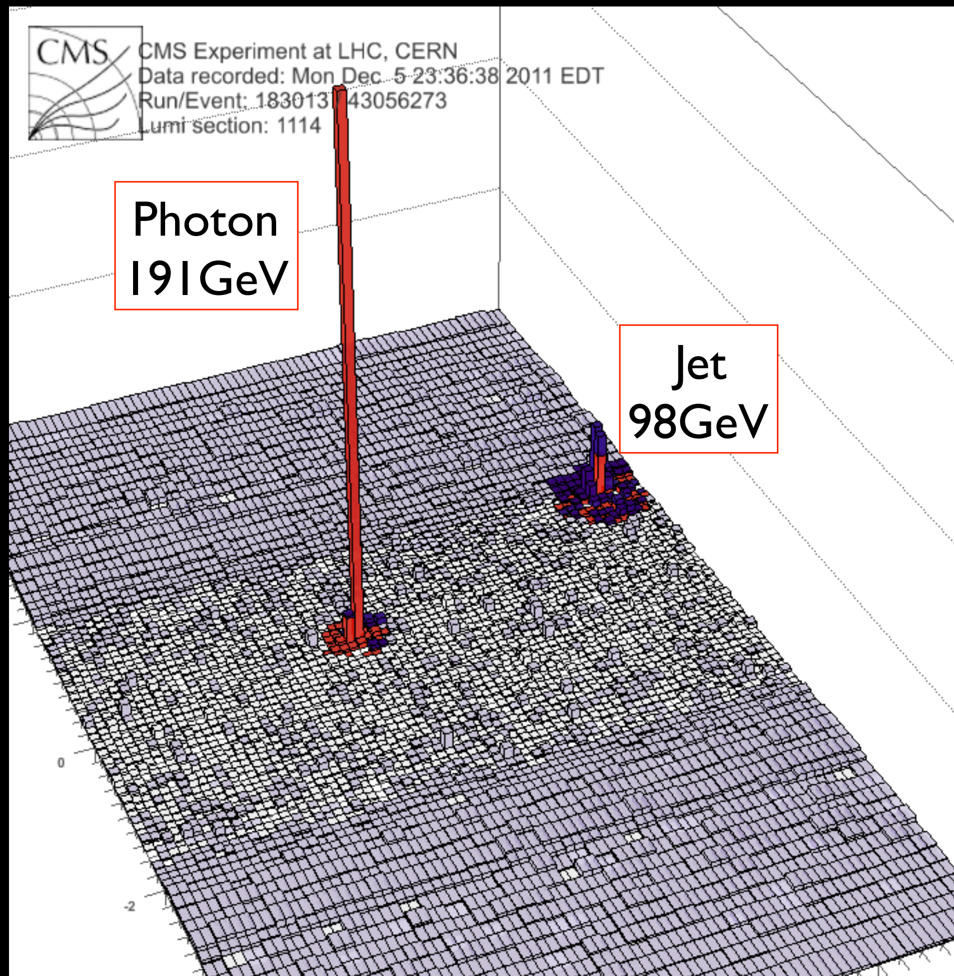
- **We need further, more discriminating, observables.**
- **We need a more precisely measured observables, to tighten the determination of the one free parameter in the hybrid model, making all the colored bands in Dani's plots tighter.**
- **And, we need to add "transverse momentum broadening", since jet quenching is not only about energy loss... And since the microscope we are looking for may be more easily found in the physics of transverse kicks than in the physics of parton energy loss ...**
- **Next: five old slides with one, naive, idea. The challenge today is to do better.**

How to see weakly Coupled q & g in Liquid QGP

D'Eramo, Lekaveckas, Liu, Rajagopal, 1211.1922

- **We *know* that at a short enough length scale, QGP *is* made of weakly coupled quarks and gluons, even though on its natural length scales QGP is a strongly coupled fluid with no quasiparticles.**
- **Long-term challenge: understand *how* liquid QGP emerges from an asymptotically free theory.**
- **First things first: how can we see the point-like quarks and gluons at short distance scales? Need a 'microscope'. Need to look for large-angle scattering not as rare as it would be if QGP were liquid-like on all length scales. (Think of Rutherford.)**
- **γ-jet events: γ tells you initial direction of quark. Measure deflection angle of jet. Closest analogy to Rutherford. (Today, only thousands of events. Many more ~ 2015.)**

2011: Detected 3000 photon-jet pairs in 10^9 PbPb collisions



Unbalanced photon-jet event in PbPb

Momentum Broadening in Weakly Coupled QGP

Calculate $P(k_\perp)$, the probability distribution for the $k_\perp$ that a parton with energy $E \to \infty$ picks up upon travelling a distance L through the medium:

- $P(k_\perp) \propto \exp(-\# k_\perp^2/(T^3 L))$ **in strongly coupled plasma. Qualitative calculation, done via holography.**

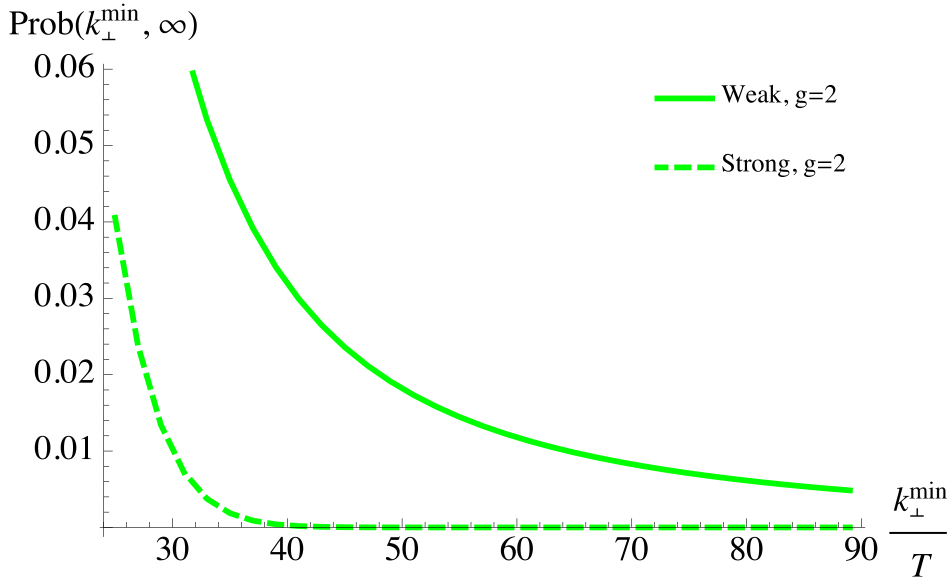
  D'Eramo, Liu, Rajagopal, arXiv:1006.1367

- **For a weakly coupled plasma containing point scatterers $P(k_\perp) \propto 1/k_\perp^4$ at large $k_\perp$. In the strongly coupled plasma of an asymptotically free gauge theory, this must win at large enough $k_\perp$. Quantitative calculation, done using Soft Collinear Effective Theory + Hard Thermal Loops.**

  D'Eramo, Lekaveckas, Liu, Rajagopal, arXiv:1211.1922

Expect: Gaussian at low $k_\perp$; power-law tail at high $k_\perp$.

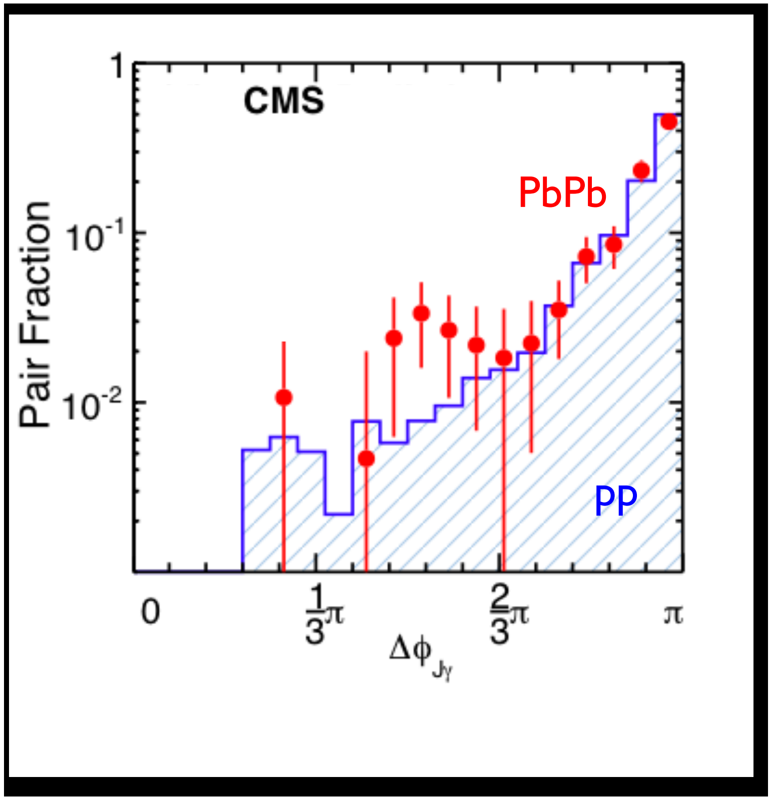
Large deflections rare, but not as rare as if the liquid were a liquid on all scales. They indicate point-like scatterers.



D'Eramo, Lekaveckas, Liu, Rajagopal, arXiv:1211.1922

- **Probability that a parton that travels $L = 7.5/T$ through the medium picks up $k_\perp > k_{\perp\mathrm{min}}$, for:**
  - **Weakly coupled QCD plasma, in equilibrium, analyzed via SCET+HTL. With $g = 2$, i.e. $\alpha_{\mathrm{QCD}} = 0.32$.**
  - **Strongly coupled $\mathcal{N} = 4$ SYM plasma, in equilibrium, analyzed via holography. With $g = 2$, i.e. $\lambda_{\mathrm{'t\ Hooft}} = 12$.**
- **Eg, for $T = 300$ MeV, $L = 5$ fm, a 60 GeV parton that picks up $70\,T$ of $k_\perp$ scatters by 20°. Presence of point-like scatterers gives this a probability $\sim 1\%$, as opposed to negligible.**

Measure the angle between jet and photon



CMS, arXiv:1205.0206

Need many more events before this can be a "QGP Rutherford Experiment". Something to look forward to circa 2015?

That calculation was naive . . .

- Calculation of $P(k_\perp)$ above neglected vacuum radiation: eg three-jet events look like large angle scattering.
- Very recently, Kurkela and Wiedemann (1407.0293) have shown that, parametrically, there is a window in scattering angle where single large angle scattering off the quasiparticles in a weakly coupled plasma dominates over both vacuum radiation and the Gaussian at small $k_\perp$.
- The idea that $P(k_\perp)$ is Gaussian at small $k_\perp$ (all $k_\perp$ in a theory that is strongly coupled at all scales) and, in an asymptotically free gauge theory, has a power-law tail at large $k_\perp$ coming from vacuum radiation plus scattering off individual quasiparticles is sound. Needs calculation.
- Regardless, certainly we need separate access to energy loss and the Gaussian momentum broadening. Adding Gaussian momentum broadening, with one new parameter(?), to the hybrid model is on the agenda. What data should we use to fix that new parameter?
- Better ideas on how to see the quasiparticles that must be present at short length scales??

Two Early Lessons from Holographic Calculations . . .

- **'Jet quenching parameter' $\hat{q}$ (mean k_T^2 picked up per distance travelled) *not* proportional to "number of scattering centers", which is $\propto N_c^2$.** Liu, Rajagopal, Wiedemann, 2006

$$\hat{q} \propto \sqrt{g^2 N_c} T^3$$

After all, there are no scattering centers if the liquid is strongly coupled on all length scales.

- **Heavy quarks with mass M lose energy via drag, or friction,** Gubser, 2006; Herzog, Karch, Kovtun, Kozcaz, Yaffe, 2006; Casalderrey-Solana, Teaney, 2006

$$\frac{dE}{dt} \propto -E \frac{\pi\sqrt{g^2 N_c}}{2} \frac{T^2}{M} , \qquad \frac{\langle k_T^2 \rangle}{\text{time}} \propto 2\pi\gamma\sqrt{g^2 N_c} T^3$$

and then diffuse with $D \propto 2/(\pi\sqrt{\lambda}T)$. So, the heavy quarks quickly end up "going with the flow". Lost energy becomes sound waves. This latter is generic (to energy loss of anything) in strongly coupled liquid.

. . . and Two Big Holes in our Understanding

- **The heavy quark results are valid for a quark of mass M whose Lorentz γ satisfies**

$$\gamma < \left(\frac{M}{\sqrt{g^2 N_c T}} \right)^2 \quad .$$

  Eg, valid if you first take $M \to \infty$ and second take γ large. Eg, if $M = 4.2$ GeV, $g^2 N_c = 10$, $T = 0.5$ GeV it is valid for $\gamma = E/M < 7$. Higher energy heavy quarks behave like light quarks.

- **The $\widehat{q}$ calculation is done for a quark or gluon on the light cone. You must first take $\gamma \to \infty$. M doesn't matter.**
- **Hole: no holographic calculation exists that bridges the above two, i.e. valid for γ below and above $M^2/g^2 N_c T^2$.**
- **Hole: no holographic calculation exists that tells us what to use for $\langle k_\perp^2 \rangle$ for the light partons in the PYTHIA shower in our hybrid model as they lose most of their energy.**

One more Hole/Opportunity

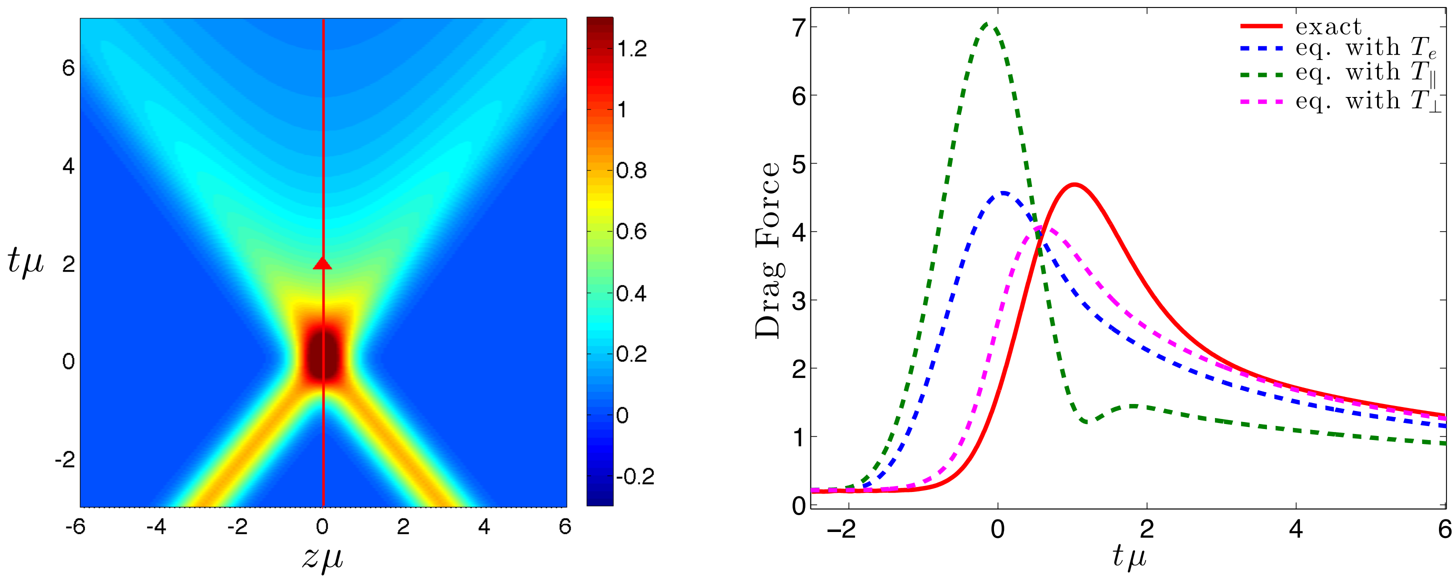
- Not our subject today, but there has been a lot of recent work on equilibration, better called hydrodynamization, in strongly coupled gauge theories, starting from a wide range of different initial conditions. For example, in the collision of sheets or disks of cold strongly coupled matter.

- We have studied the drag force on a heavy quark in the early far-from-equilibrium epoch in such a collision, and in the expanding cooling plasma that results.

- Nobody has yet done the "jet" quenching calculation with which I began my first talk in such a background. It is a well-posed, but nontrivial, calculation that could give us qualitative insights into the importance of the early far-from-equilibrium epoch for jet quenching phenomena.

Heavy Quark Energy Loss, Far-from-Equilibrium

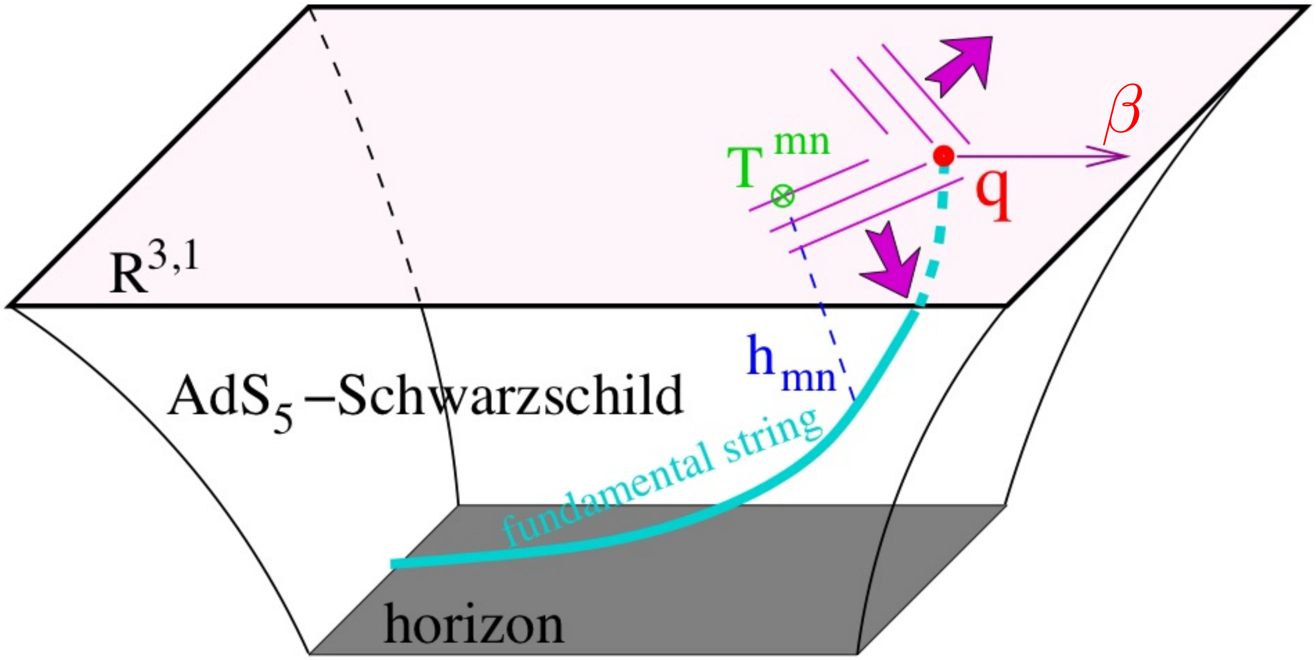
Chesler, Lekaveckas, Rajagopal 1306.0564



- **Drag force on a heavy quark moving with $\beta = 0.95c$ through far-from-equilibrium matter, and then anisotropic fluid, made in the collision of two sheets of energy in strongly coupled $\mathcal{N} = 4$ SYM theory.**
- **Guidance for modeling heavy quark energy loss early in a heavy ion collision: at mid-rapidity, eqbm plasma with same instantaneous $\mathcal{E}$ provides reasonable guide to magnitude, but there is a time delay. Surprises at nonzero rapidity. (Not shown. 'Surfing' on a gradient.)**
- **Analytic calculation of effect of $\vec{\nabla} v^{\text{fluid}}$ on energy loss is possible. We have done this to first order in gradients, which describes the effects well.** Lekaveckas, Rajagopal, 1311.5577.

Dragging a Heavy Quark through Strongly Coupled Plasma

HKKKY, G, 2006



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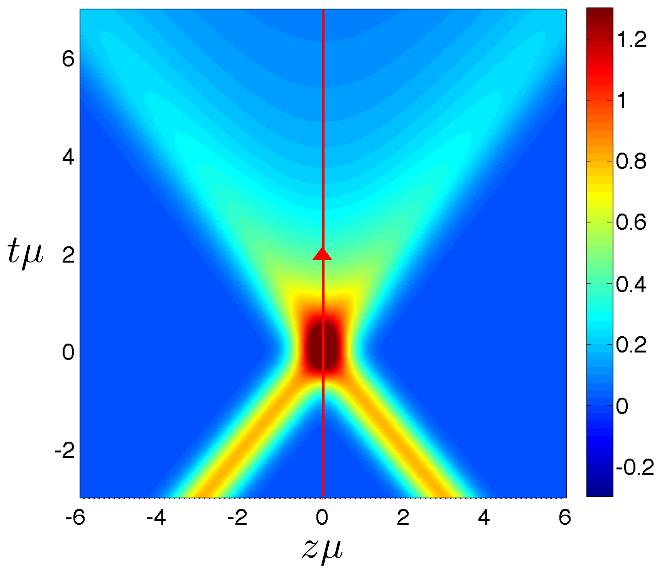

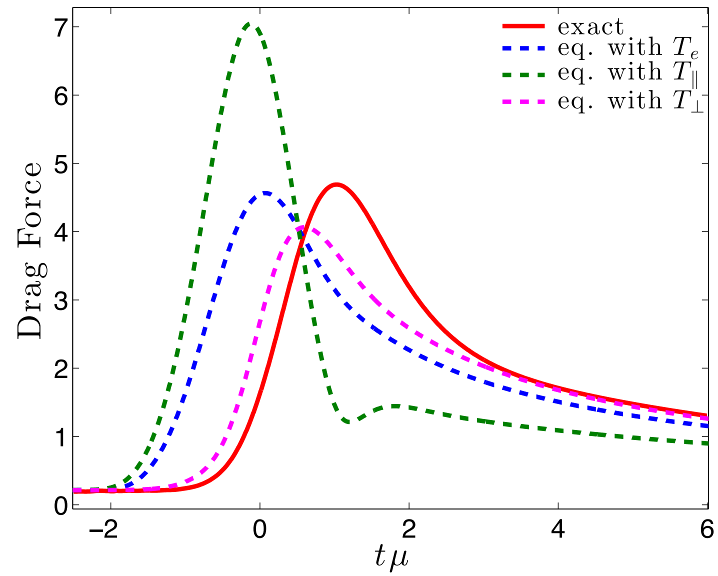

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- We have studied the drag force on a heavy quark in the early far-from-equilibrium epoch in such a collision, and in the expanding cooling plasma that results.

- Nobody has yet done the “jet” quenching calculation with which I began my first talk in such a background. It is a well-posed, but nontrivial, calculation that could give us qualitative insights into the importance of the early far-from-equilibrium epoch for jet quenching phenomena.

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.

9781107022461 CASALDERREY-SOLANA ET AL – GAUGE/STRING DUALITY, HOT QCD AND HEAVY ION COLLISIONS C M Y K

Heavy ion collision experiments recreating the quark–gluon plasma that filled the microseconds-old universe have established that it is a nearly perfect liquid that flows with such minimal dissipation that it cannot be seen as made of particles. String theory provides a powerful toolbox for studying matter with such properties.

This book provides a comprehensive introduction to gauge/string duality and its applications to the study of the thermal and transport properties of quark–gluon plasma, the dynamics of how it forms, the hydrodynamics of how it flows, and its response to probes including jets and quarkonium mesons.

Calculations are discussed in the context of data from RHIC and LHC and results from finite temperature lattice QCD. The book is an ideal reference for students and researchers in string theory, quantum field theory, quantum many-body physics, heavy ion physics, and lattice QCD.

Jorge Casalderrey-Solana is a Ramón y Cajal Researcher at the Universitat de Barcelona. His research focuses on the properties of QCD matter produced in ultra-relativistic heavy ion collisions.

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Krishna Rajagopal is a Professor of Physics at MIT. His research focuses on QCD at high temperature or density, where new understanding can come from unexpected directions.

Urs Achim Wiedemann is a Senior Theoretical Physicist at CERN, researching the theory and phenomenology of ultra-relativistic heavy ion collisions.

Cover illustration: an artist's impression of the hot matter produced by a heavy ion collision falling into the black hole that provides its dual description. Created by Mathias Zwygart and inspired by an image, courtesy of the ALICE Collaboration and CERN.

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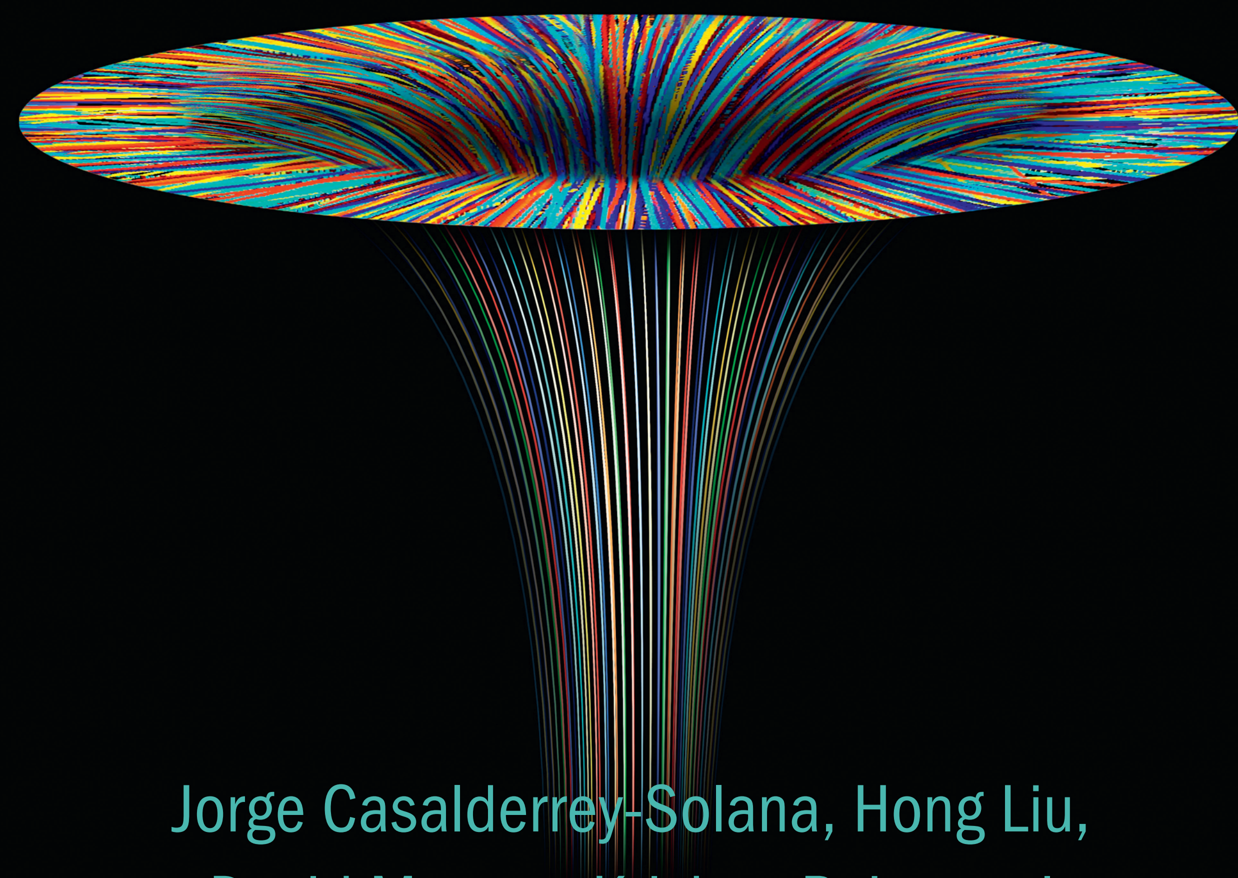

Jorge Casalderrey-Solana, Hong Liu, David Mateos, Krishna Rajagopal and Urs Achim Wiedemann

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Contents

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.