

# Jet Quenching in Strongly Coupled Plasma

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based upon arXiv:1402.6756, by Paul Chesler 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 next 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 the lost energy?

- Initially, hydrodynamic modes with wave vector  $\lesssim \pi T$ .
- 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 have thermalized, becoming soft particles in random directions. Only the 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. Should be easier to see in lower temperature plasma, where  $x_{\text{damping}}^{\text{sound}}$  is longer.

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# One More Question

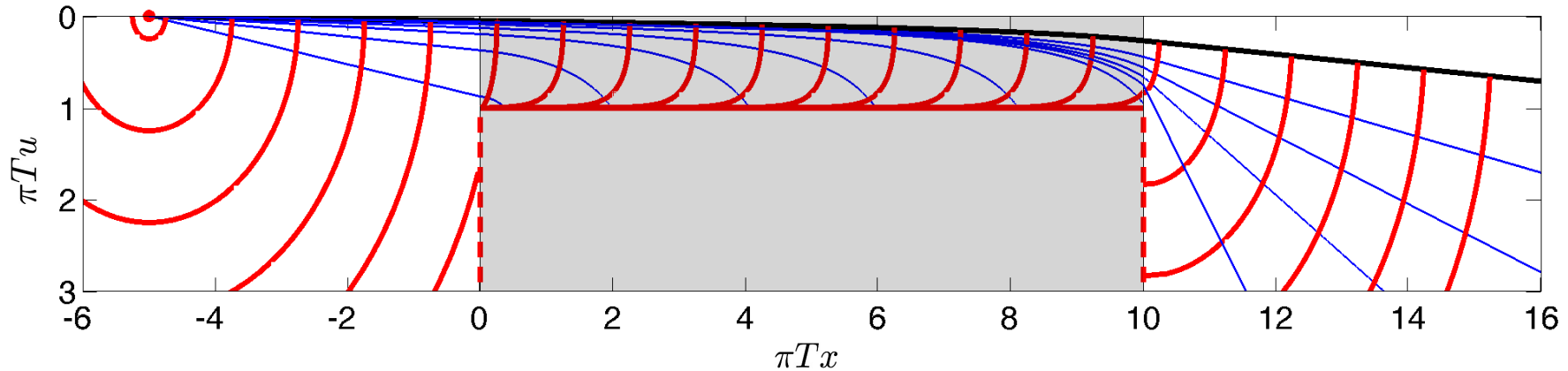
- So, why did I write “jets” instead of jets? Which is to say, what is a jet in  $\mathcal{N} = 4$  SYM theory, anyway? There is no one answer, because hard processes in  $\mathcal{N} = 4$  SYM theory don’t make jets. Hatta, Iancu, Mueller; Hofman, Maldacena.
- The formation of (two) highly virtual partons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

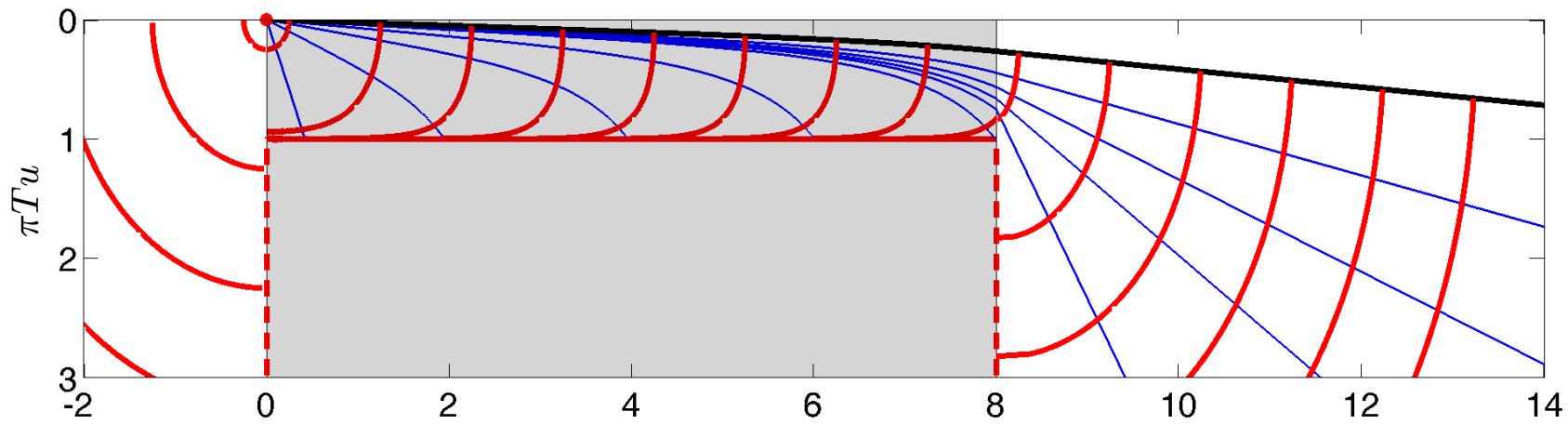


A light quark “jet”, incident with  $E_{\text{in}}$ , shoots through a slab of strongly coupled  $\mathcal{N} = 4$  SYM plasma, temperature  $T$ , thickness  $L\pi T = 10$ , assumed  $\gg 1$ . What comes out the other side? A “jet” with  $E_{\text{out}} \sim 0.64E_{\text{in}}$ ; just like a vacuum “jet”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

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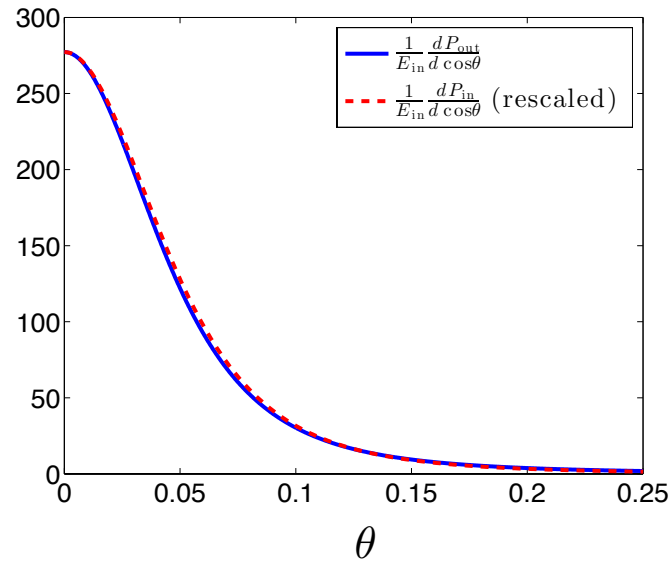
Here, a light quark ‘jet’ produced next to the slab of plasma with incident energy  $E_{\text{in}} = 87\sqrt{\lambda}\pi T \sim 87\sqrt{\lambda}$  GeV shoots through the slab and emerges with  $E_{\text{out}} \sim 66\sqrt{\lambda}$  GeV. Again, the “jet” that emerges looks like a vacuum “jet” with that 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  $\sigma$  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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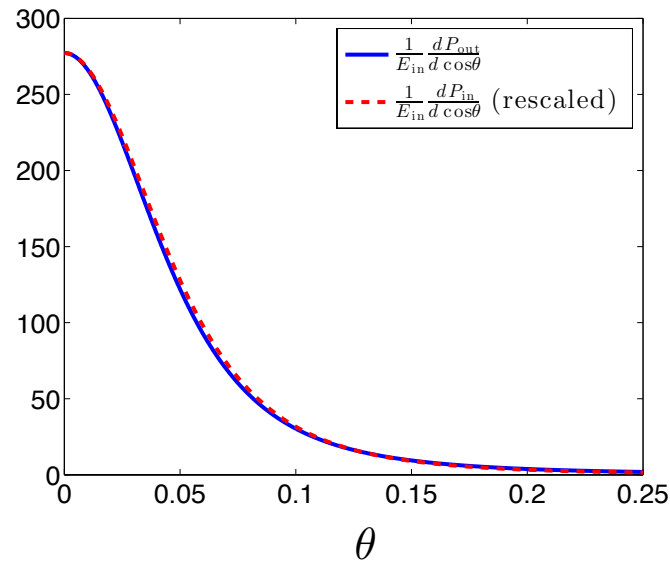


Shape of outgoing “jet” is the same as incoming “jet”, except broader in angle and less total energy.

We have computed the energy flow infinitely far downstream from the slab, as a function of the angle  $\theta$  relative to the “jet” direction.

# Quenching a Light Quark “Jet”

Chesler, Rajagopal, 1402.6756



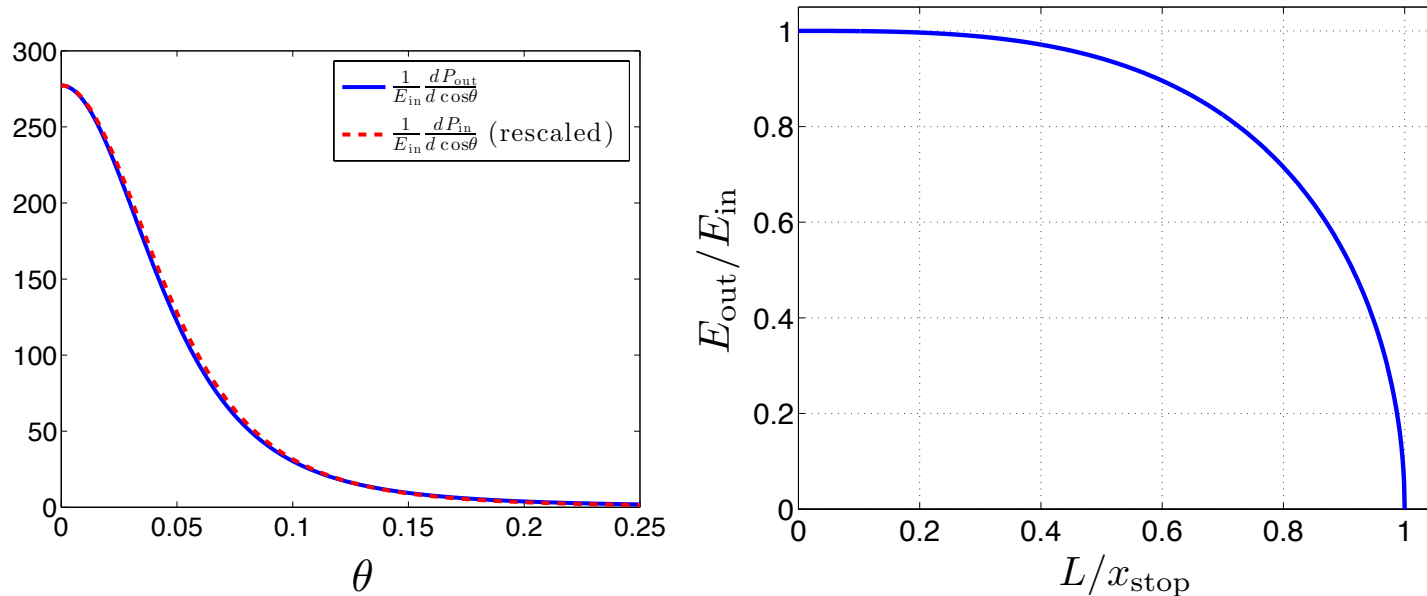
Blue curve is angular shape of the “jet” that emerges from the slab after having been quenched.

Red dashed curve is shape of vacuum “jet”, in the absence of any plasma, with  $\theta$  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:

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

where  $\pi T x_{stop} \propto (E_{in}/(\sqrt{\lambda} \pi T))^{1/3}$ . 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  $dE_{\text{out}}/dL$  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”:

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

where

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

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  $\theta_{\text{jet}} \equiv m_{\text{jet}}/E_{\text{jet}} \equiv \sqrt{E_{\text{jet}}^2 - p_{\text{jet}}^2}/E_{\text{jet}}$ ? Easy for us to calculate. But, are there better definitions of  $\theta_{\text{jet}}$  that don't require summing over all the tracks, given that we have the whole profile?
- QCD predicts the distribution of  $m_{\text{in}}$  (eg  $\theta_{\text{in}}$ ) for each  $E_{\text{in}}$ .  $\mathcal{N} = 4$  SYM does not; each must be specified separately. Send an ensemble of “jets”, with  $\theta_{\text{in}}$  for each  $E_{\text{in}}$  distributed as in QCD, through the brick of plasma. For each “jet”,  $E_{\text{out}} < E_{\text{in}}$  and  $m_{\text{out}} > m_{\text{in}}$ . Analyze distribution of  $m_{\text{out}}$  (eg  $\theta_{\text{out}}$ ) for a given  $E_{\text{out}}$ . How similar is the distribution of  $m_{\text{out}}$  for “jets” with a given  $E_{\text{out}}$  to the distribution of  $m_{\text{in}}$  for incident “jets” with energy  $E_{\text{out}}$ ?
- Can experimentalists measure change in shape of jets in PbPb collisions relative to shape of jets with the same *initial* energy in pp collisions? Needs high statistics gamma-jet data.

# 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?
- As jets must be reconstructed with some jet radius parameter, how much does jet broadening artificially depress jet  $R_{AA}$ ?
- Redo the present analysis for a hydrodynamic solution rather than for a brick.

# Gauge/String Duality, Hot QCD and Heavy Ion Collisions

Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann

A 460 page book. We finished the manuscript a few months ago. To appear June 2014, 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.



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.

**Hong Liu** is an Associate Professor of Physics at MIT. His research interests include quantum gravity and exotic quantum matter.

**David Mateos** is a Professor at the Universitat de Barcelona, where he leads a group working on the connection between string theory and quantum chromodynamics.

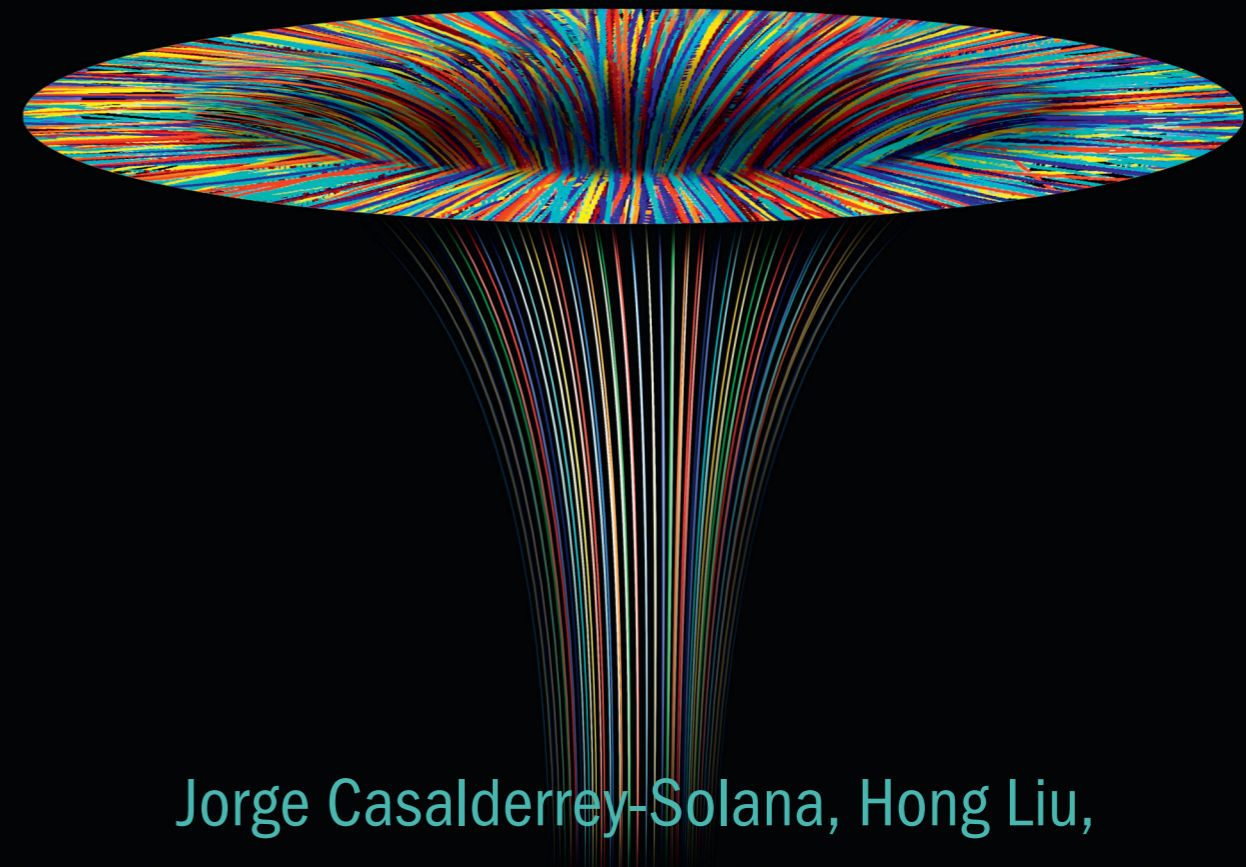
**Krishna Rajagopal** is a Professor of Physics at MIT. His research focuses on QCD at high temperature or density, where new understanding can come from unexpected directions.

**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.

Casalderrey-Solana, Liu, Mateos, Rajagopal and Wiedemann  
Gauge/String Duality, Hot QCD and Heavy Ion Collisions

# Gauge/String Duality, Hot QCD and Heavy Ion Collisions



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

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# 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  $\eta/s$  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.