Qualitative Lessons about Quark-Gluon Plasma and Heavy Ion Collisions from Holographic Calculations

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Quark-Gluon Plasma

- The $T \to \infty$ phase of QCD. Entropy wins over order; symmetries of this phase are those of the QCD Lagrangian.

- Asymptotic freedom tells us that, for $T \to \infty$, QGP must be weakly coupled quark and gluon quasiparticles.

- Lattice calculations of QCD thermodynamics reveal a smooth crossover, like the ionization of a gas, occurring in a narrow range of temperatures centered at a $T_c \simeq 175$ MeV $\simeq$ 2 trillion °C $\sim$ 20 μs after big bang. At this temperature, the QGP that filled the universe broke apart into hadrons and the symmetry-breaking order that characterizes the QCD vacuum developed.

- Experiments now producing droplets of QGP at temperatures several times T_c, reproducing the stuff that filled the few-microseconds-old universe.

Heavy Ion Collisions

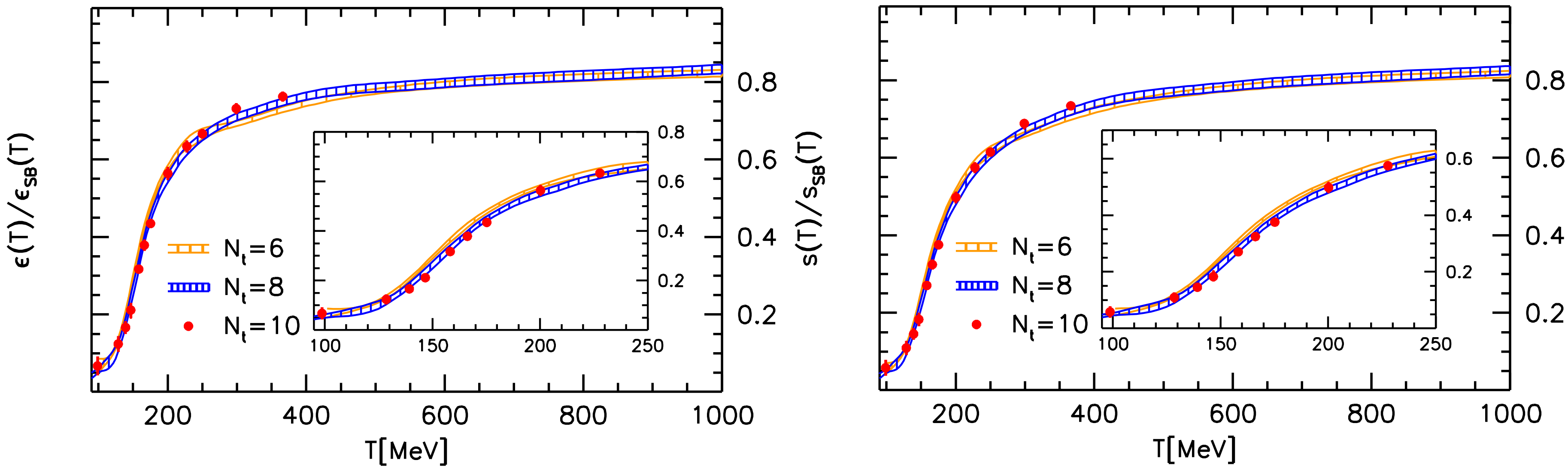
- By colliding "nuclear pancakes" (nuclei Lorentz contracted by $\gamma \sim 100$ and now $\gamma \sim 1400$), RHIC and now the LHC are making little droplets of "Big Bang matter": the stuff that filled the whole universe microseconds after the Big Bang.

- Using five detectors (PHENIX & STAR @ RHIC; ALICE, ATLAS & CMS @ LHC) scientists are answering questions about the microseconds-old universe that cannot be addressed by any conceivable astronomical observations made with telescopes and satellites.

- And, the properties of the matter that filled the microsecond old universe turn out to be interesting. The Liquid Quark-Gluon Plasma shares common features with forms of matter that arise in condensed matter physics, atomic physics and black hole physics, and that pose challenges that are central to each of these fields.

QGP Thermodynamics

Endrodi et al. 2010



Above $T_{\text{crossover}} \sim$ 150-200 MeV, QCD = QGP. QGP static properties can be studied on the lattice.

Lesson of the past decade: don't try to infer dynamic properties from static ones. Although its thermodynamics is almost that of ideal-noninteracting-gas-QGP, this stuff is very different in its dynamical properties. [Lesson from experiment+hydrodynamics. But, also from the large class of gauge theories with holographic duals whose plasmas have ε and s at infinite coupling 75% that at zero coupling, a result that goes back to 1996 that was not appreciated initially.]

Rapid Equilibration?

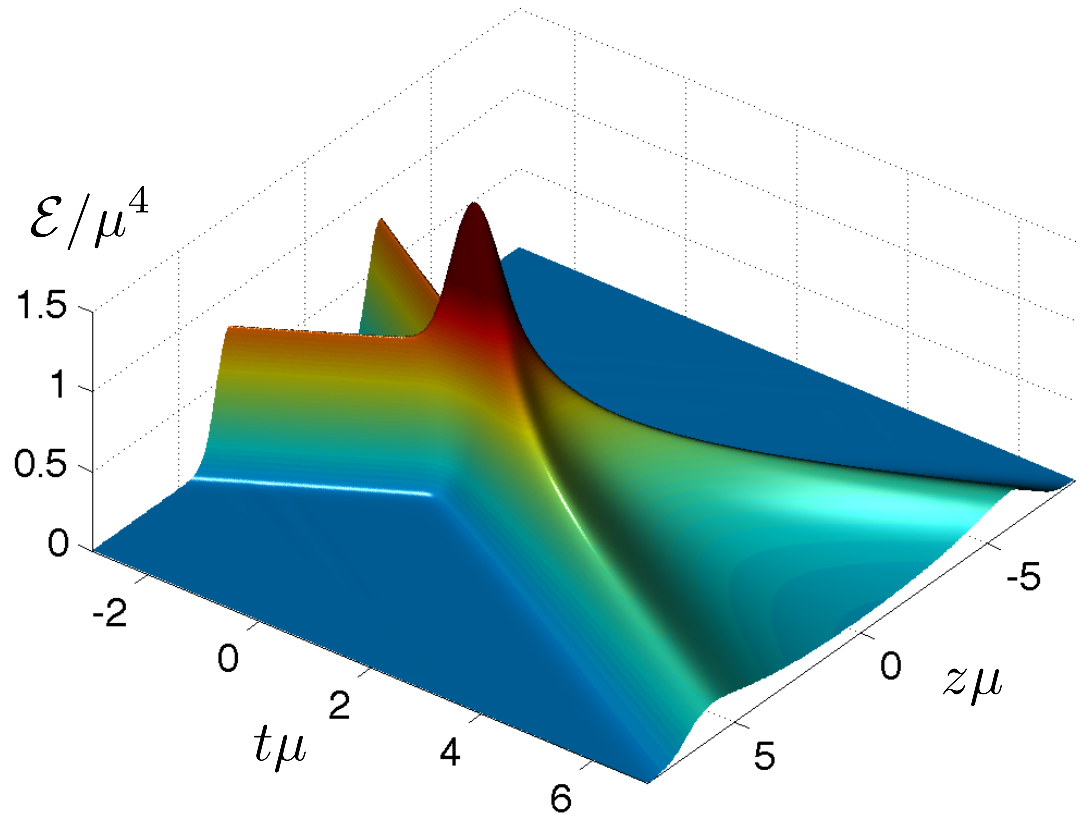
- Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large η/s) or if it takes too long for the droplet to equilibrate.

- Long-standing estimate is that a hydrodynamic description must already be valid only 1 fm after the collision.

- This has always been seen as *rapid equilibration*. Weak coupling estimates suggest equilbration times of 3-5 fm. And, 1 fm just sounds rapid.

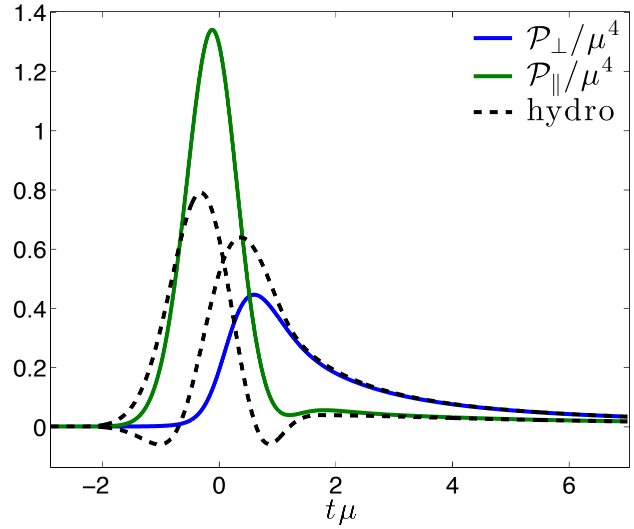
- But, is it really? How rapidly does equilibration occur in a strongly coupled theory?

Colliding Strongly Coupled Sheets of Energy



Hydrodynamics valid ~ 3 sheet thicknesses after the collision, i.e. ~ 0.35 fm after a RHIC collision. Equilibration after ~ 1 fm need not be thought of as rapid. Chesler, Yaffe 1011.3562; generalized in C-S,H,M,vdS 1305.4919; CY 1309.1439 **Similarly 'rapid' hydrodynamization times ($\tau T \lesssim 0.7 - 1$) found for *many* non-expanding or boost invariant initial conditions.** Heller and various: 1103.3452, 1202.0981, 1203.0755, 1304.5172

Anisotropic Viscous Hydrodynamics



Hydrodynamics valid so early that the hydrodynamic fluid is not yet isotropic. 'Hydrodynamization before isotropization.' An epoch when first order effects (spatial gradients, anisotropy, viscosity, dissipation) important. Hydrodynamics with entropy production.

This has now been seen in very many strongly coupled analyses of hydrodynamization. Janik et al., Chesler et al., Heller et al., ...

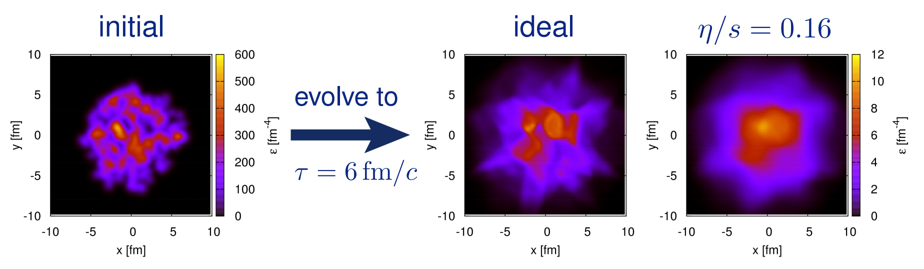
Could have been anticipated as a possibility without holography. But, it wasn't — because in a weakly coupled context isotropization happens first.

Liquid Quark-Gluon Plasma

- Hydrodynamic analyses of RHIC, and now LHC, data on how asymmetric blobs of Quark-Gluon Plasma expand (explode) have taught us that QGP is a strongly coupled liquid, with (η/s) — the dimensionless characterization of how much dissipation occurs as a liquid flows — much smaller than that of all other known liquids except one.

- The discovery that it is a strongly coupled liquid is what has made QGP interesting to a broad scientific community.

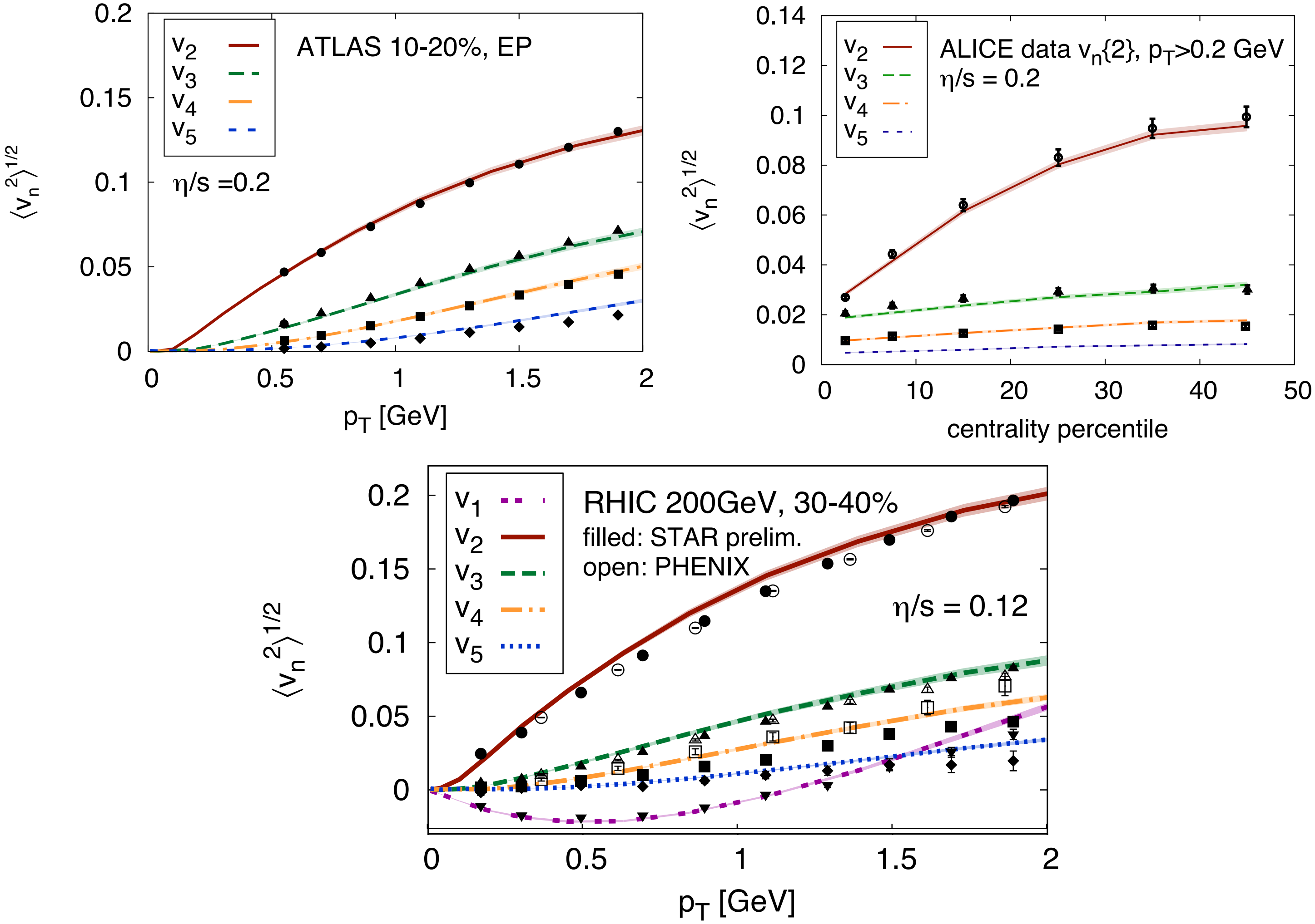
- The talk I am *not* giving today: a continuing interplay between heavy ion collision experiments and hydrodynamic theory that is steadily tightening our understanding of the properties of this liquid.



initial
evolve to
$\tau = 6\,\mathrm{fm}/c$
ideal
$\eta/s = 0.16$
x [fm]
y [fm]
ε [fm^{-4}]

Example of State-of-the-art

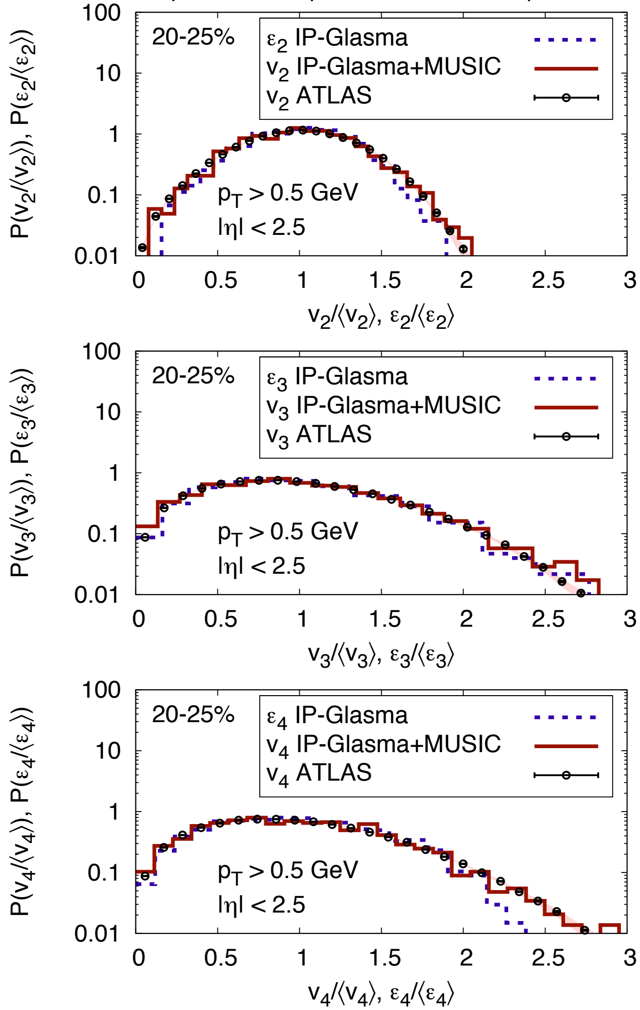
Gale, Jeon, Schenke, Tribedy, Venugopalan, 2013



Good fit to RHIC data (with $\eta/s = 0.12$) and LHC data (with $\eta/s = 0.20$) for one model of initial fluctuations, and with a simplified treatment of the hadronic final state.

Example of State-of-the-art

Gale, Jeon, Schenke, Tribedy, Venugopalan, 2013



And v_n-fluctuations in the final state too...

Systematic use of data to constrain initial fluctuations under investigation by several groups.

η/s and Holography

- $4\pi\eta/s = 1$ for any (of the very many) known strongly coupled large-N_c gauge theory plasmas that are the "hologram" of a (4+1)-dimensional gravitational theory "heated by" a (3+1)-dimensional black-hole horizon.
- Geometric intuition for dynamical phenomena at strong coupling. Hydrodynamization = horizon formation. Nontrivial hydrodynamic flow pattern = nontrivial undulation of black-hole metric. Dissipation due to shear viscosity = gravitational waves falling into the horizon.
- Conformal examples show that hydrodynamics need not emerge from an underlying kinetic theory of particles. A liquid can just be a liquid.
- $1 < 4\pi\eta/s < 3$ for QGP at RHIC and LHC.
- Suggests a new kind of universality, not yet well understood, applying to dynamical aspects of strongly coupled liquids. To which liquids? Unitary Fermi 'gas'?

Hydrodynamics in pPb collisions?

- Almost nobody expected this. pPb collisions supposed to be a control experiment. Too small for hydrodynamics.
- But, how large *is* the 'hot-spot' made when a proton blasts through a nucleus? Maybe as large as 2-3 fm across?? [Bozek] Hydrodynamics can work if equilibration time much less than this. This is the case in the strongly coupled plasmas with a holographic description. Further evidence for the strongly coupled liquid nature of QGP?
- What are we selecting for when we select high multiplicity pPb collisions? Not just impact parameter. Quantum fluctuations of the proton important? Maybe we are selecting 'fat protons'?
- And, PHENIX has now gone back, looked for, and found v_2 in d-Au collisions at RHIC.
- Experimental and theoretical investigations still in progress. Systematic investigation of initial conditions now requires confronting PbPb and pPb data at LHC and RHIC.

Why care about the value of η/s?

- **Here is a theorist's answer...**

- **Any gauge theory with a holographic dual has $\eta/s = 1/4\pi$ in the large-N_c, strong coupling, limit. In that limit, the dual is a classical gravitational theory and η/s is related to the absorption cross section for stuff falling into a black hole. If QCD has a dual, since $N_c = 3$ it must be a string theory. Determining $(\eta/s) - (1/4\pi)$ would then be telling us about string corrections to black hole physics, in whatever the dual theory is.**

- **For fun, quantum corrections in dual of $\mathcal{N} = 4$ SYM give:**

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + \frac{15\,\zeta(3)}{(g^2N_c)^{3/2}} + \frac{5}{16}\frac{(g^2N_c)^{1/2}}{N_c^2} + \ldots\right)$$

Myers, Paulos, Sinha

with $1/N_c^2$ and N_f/N_c corrections yet unknown. Plug in $N_c = 3$ and $\alpha = 1/3$, i.e. $g^2N_c = 12.6$, and get $\eta/s \sim 1.73/4\pi$. And, $s/s_{SB} \sim 0.81$, near QCD result at $T \sim 2 - 3T_c$.

- **A more serious answer...**

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 other observables in 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.

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;...

- Emerging hints of how to look at matter in which quasiparticles have disappeared and quantum entanglement is enhanced: "many-body physics through a gravitational lens." Black hole descriptions of liquid QGP and strange metals are continuously related! But, this lens is at present still somewhat cloudy...

A Grand 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 two big advantages: (i) direct experimental access to the fluid of interest without extraneous degrees of freedom; (ii) weakly-coupled quark and gluon quasiparticles at short distances.
- We can quantify the properties and dynamics of Liquid QGP at its natural length scales, where it has no quasiparticles.
- Can we 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.
- The LHC and newly upgraded RHIC offer new probes and open new frontiers.

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

$$\frac{dE}{dt} \propto -E\,\frac{T^2}{M}\ ,$$

and then diffuse with $D \sim 1/(2\pi T)$. 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; more below.

Dragging a Heavy Quark through Strongly Coupled Plasma

HKKKY, G, 2006

- **One of the first holographic calculations related to *probing* strongly coupled plasma.**

- **To drag a heavy quark, $M \to \infty$, with constant velocity $\vec{\beta}$ through the static, homogeneous, equilibrium strongly coupled plasma with temperature T of $\mathcal{N} = 4$ SYM theory requires exerting a *drag force*:**

$$\vec{f} = \frac{\sqrt{\lambda}}{2\pi} (\pi T)^2 \gamma \vec{\beta} \propto \frac{\vec{p}}{M}$$

  with $\lambda \equiv g^2 N_c$ the 't Hooft coupling.

- ***Caveat emptor:* At finite M, this picture only applies for**

$$\sqrt{\gamma} \ll \frac{M}{T\sqrt{\lambda}} \ .$$

  Eg for b quarks at the LHC validity is $p_T \lesssim 20 - 40$ GeV. Higher p_T heavy quarks behave like light quarks.

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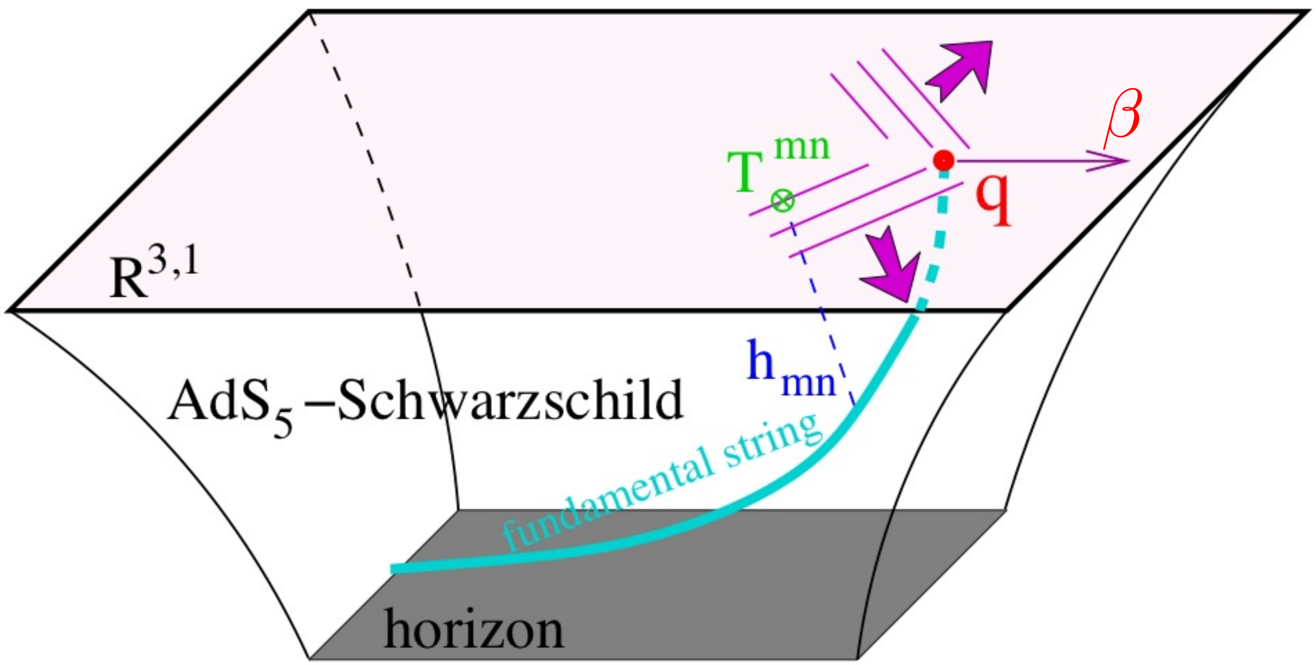

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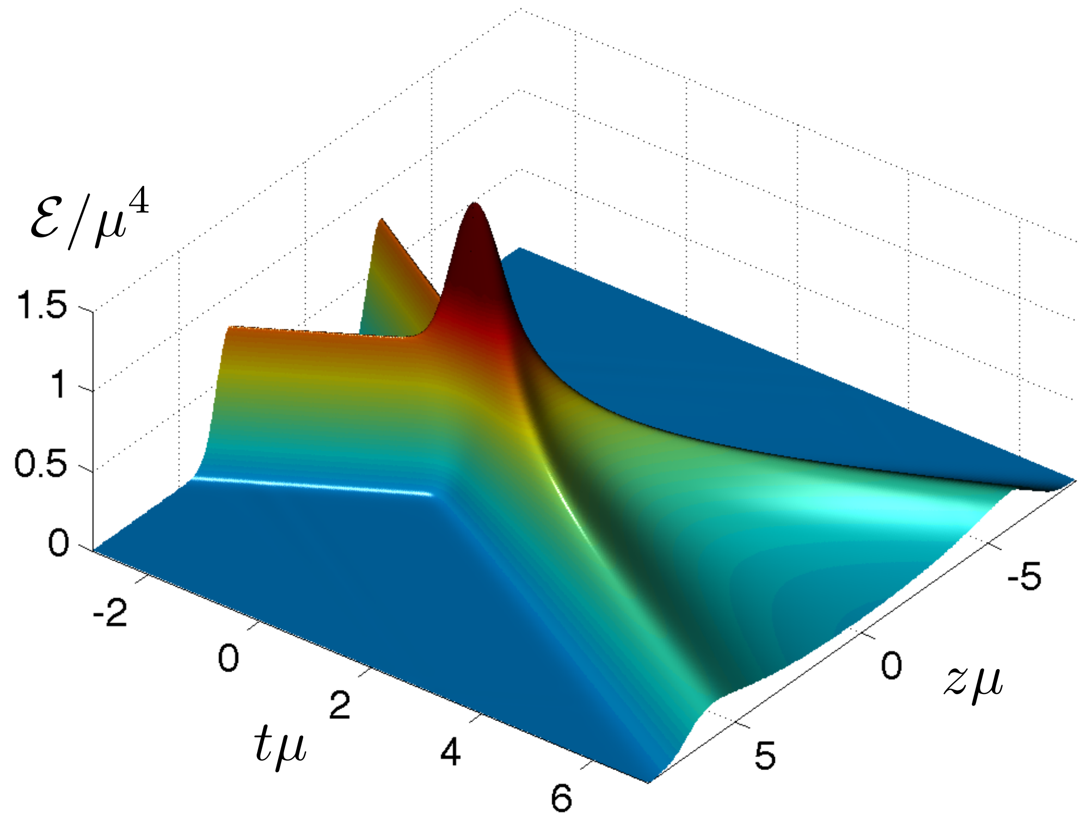
Dragging a Heavy Quark through Strongly Coupled Plasma

- The basic picture of how heavy quarks behave in strongly coupled plasma is that first they lose energy (to heat and sound in the plasma, the latter itself quickly becoming heat) and then many of them end up diffusing with diffusion constant $D \approx 1/(2\pi T)$, which is to say a very short mean free path if a mean free path can even be defined. Ie many of them end up "going with the flow".
- Heavy quarks with the same p/M have the same dp/dt.
- *Caveat emptor:* the fluid produced in heavy ions is not homogeneous, and although hydrodynamized it is not in static equilibrium.
- How do gradients in the fluid and temporal variations of the fluid (lets call both together "fluid gradients") affect the drag force? Ripples in the fluid become ripples in the horizon and metric. Those cause the string to ripple. That affects the drag force.

Colliding Strongly Coupled Sheets of Energy



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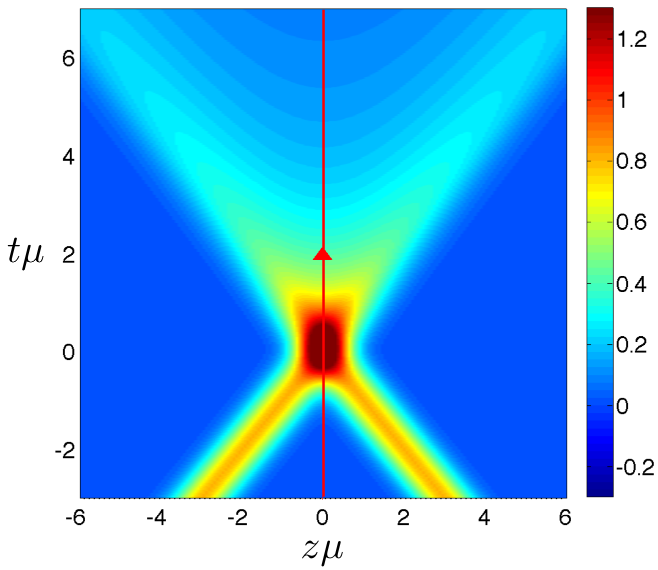
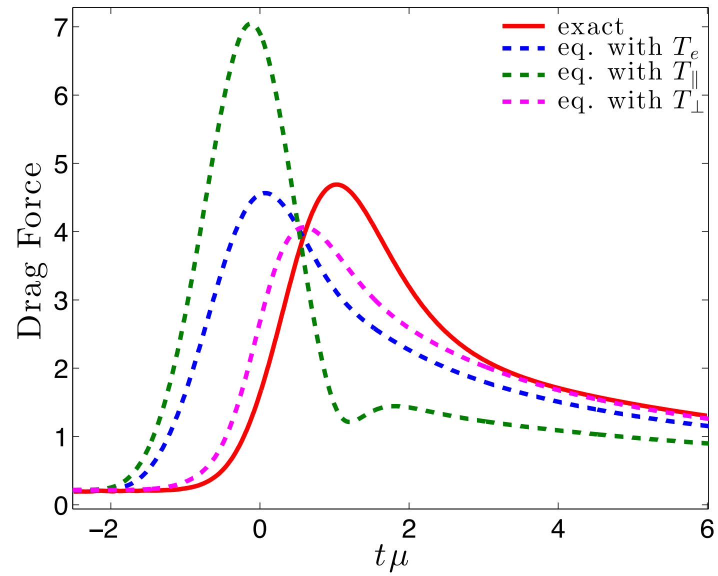
Heavy Quark Energy Loss, Far-from-Equilibrium

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 expectations provide a reasonable guide to magnitude, but there is a time delay. Surprises at nonzero rapidity. (Discuss later).**
- **Analytic calculation of effect of $\vec{\nabla} v^{\text{fluid}}$ on energy loss is possible. We have done this to first order in gradients.** Lekaveckas, Rajagopal, 1311.5577.

Effects of Fluid Gradients on Drag

Lekaveckas, Rajagopal, 1311.5577

- **Some notation:** $b \equiv 1/(\pi T_e)\,,$

  where T_e is defined from ε via $\varepsilon = (3\pi^2/8)N_c^2 T_e^4$.

  Fluid four-velocity: $u^\mu = \gamma_v(1, \vec{v})$.

  Heavy quark four-velocity: $w^\mu = \gamma(1, \vec{\beta})$.

  The one Lorentz-scalar with no ∂ is: $s \equiv u^\mu w_\mu$.

  All these quantities vary in space and time.

- **Write the drag force as an expansion in powers of $\partial_\alpha u_\beta$, to first order:**

$$f^\mu = f^\mu_{(0)} + f^\mu_{(1)} + \ldots$$

  (Note: use first order viscous hydro to relate $\partial_\alpha b$ to $\partial_\alpha u_\beta$; expansion is in powers of gradients of T and v_{fluid}.)

- **We already have $f^\mu_{(0)}$: drag force to zeroth order in gradients is drag force in homogeneous plasma**

$$f^\mu_{(0)} = -\frac{\sqrt{\lambda}}{2\pi}\frac{1}{\gamma b^2}\left(s\, w^\mu + u^\mu\right)$$

Effects of Fluid Gradients on Drag

Lekaveckas, Rajagopal, 1311.5577

- **We obtain a fully general result for $f^\mu_{(1)}$:**

$$f^\mu_{(1)} = -\frac{\sqrt{\lambda}}{2\pi}\frac{1}{b\gamma}\Big[c_1(s)\Big(u^\mu w^\alpha \partial_\alpha s - s\partial^\mu s - s(s\, u^\alpha + w^\alpha)\partial_\alpha U^\mu\Big)$$

$$+c_2(s) U^\mu \partial_\alpha u^\alpha - \sqrt{-s}\, u^\alpha \partial_\alpha U^\mu\Big]$$

where

$$U^\mu \equiv u^\mu + s\, w^\mu$$

$$c_1(s) \equiv \frac{1}{4}\left[2\arctan\left(\frac{1}{\sqrt{-s}}\right) - \log\left(\frac{(1-s)(1+\sqrt{-s})^2}{s^2}\right)\right]$$

$$c_2(s) \equiv \frac{1}{3}\Big(\sqrt{-s} + (1+s^2)c_1(s)\Big)$$

This is for any configuration of fluid flow, to lowest order in gradients.

Effects of Fluid Gradients on Drag

Lekaveckas, Rajagopal, 1311.5577

- **For a quark at rest, in a fluid that is instantaneously at rest but has $\partial_t u^3 \neq 0$, we find $f^z_{(1)} = (\sqrt{\lambda}/2\pi b)\partial_t u^3$. This is exactly the value of the drag force a time $\Delta t = b$ ago. A very simple example of time delay in the response of the drag force to changing fluid conditions.**

- **Suppose the fluid is expanding à la Bjorken, in the z-direction. Suppose that, in the fluid rest frame, the heavy quark starts at $z = t = 0$ and has $\beta_x \neq 0$. Then,**

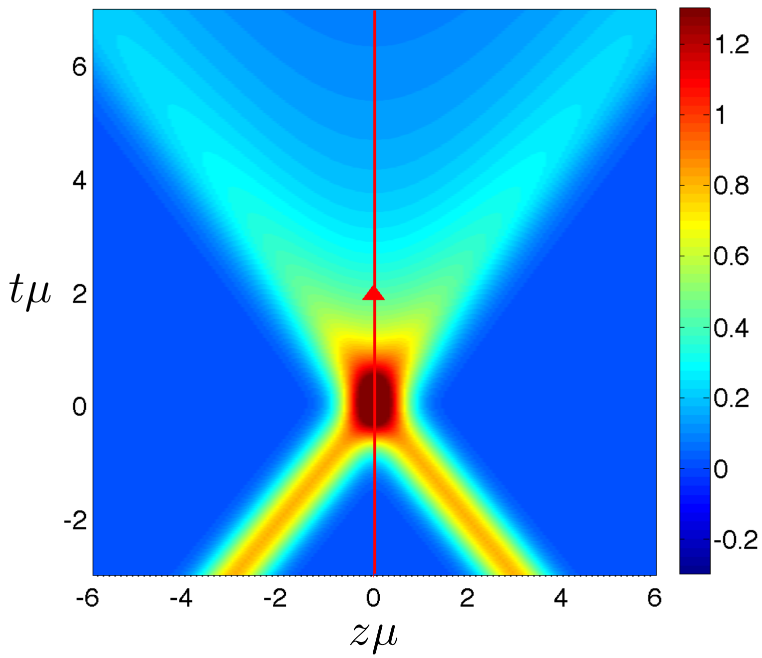
$$f^x = \frac{\sqrt{\lambda}}{2\pi}\frac{\gamma\beta_x}{b(\tau)^2}\left(1 + \frac{b(\tau)}{\tau}c_2(-\gamma)\right)$$

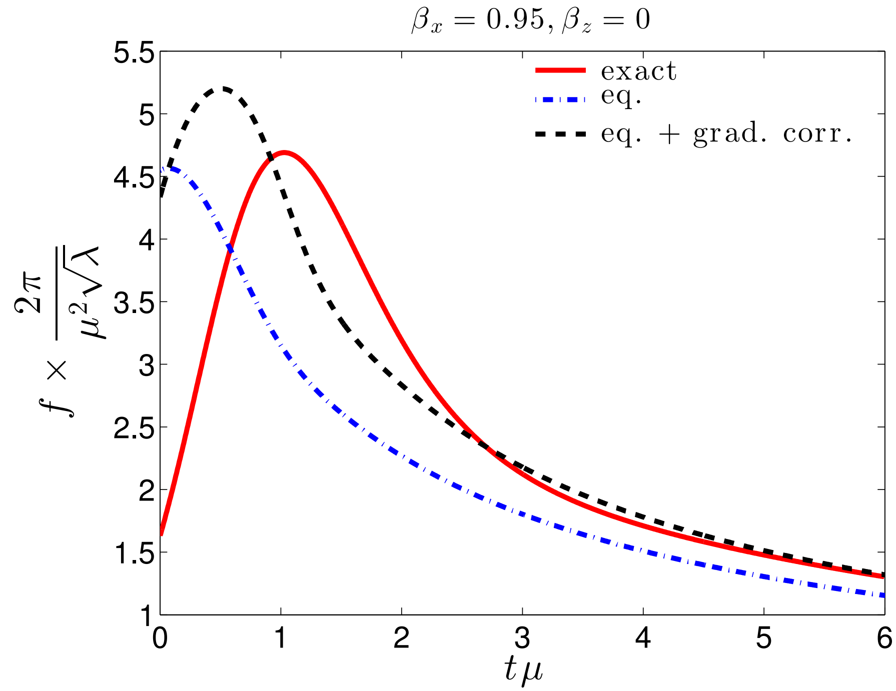
  Results in other frames and for other directions of motion of the quark in the paper.

- **And, results for the heavy quark that finds itself in the middle of those colliding sheets, after hydrodynamization...**

Heavy Quark Energy Loss, Zero-Rapidity

Lekaveckas, Rajagopal 1311.5577

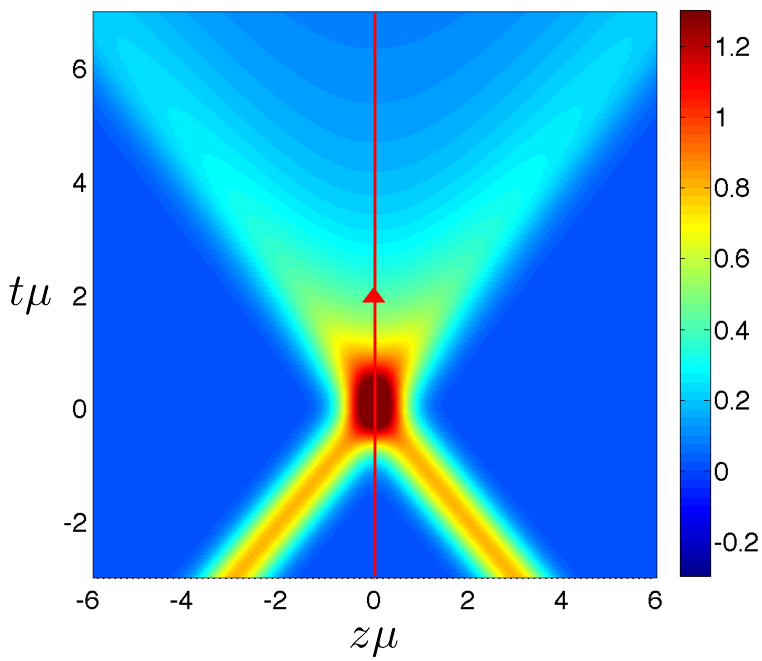


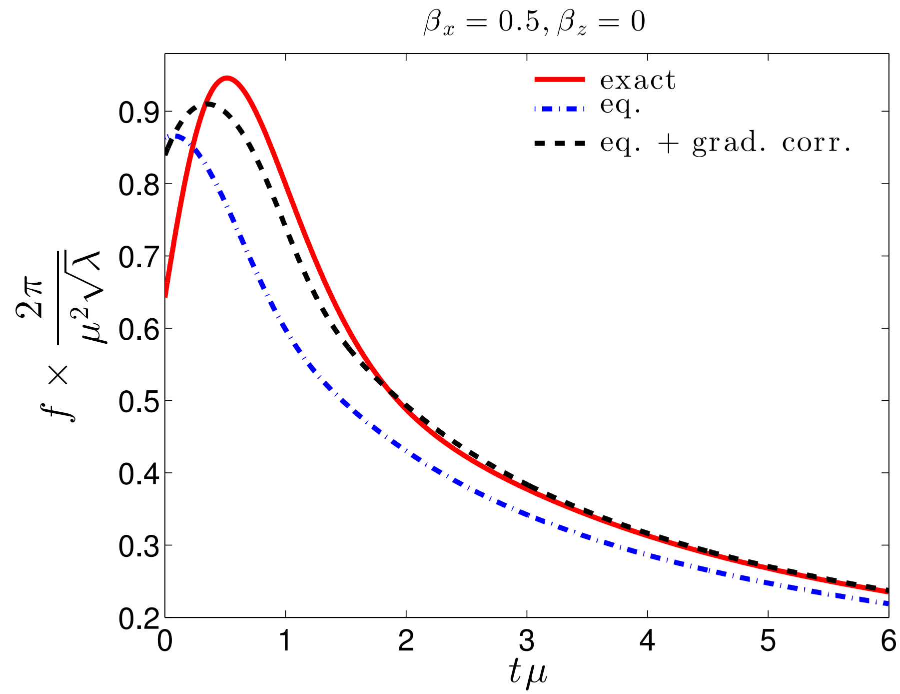


- **After hydrodynamization, first order contribution to drag force does a very good job of describing the discrepancy identified previously.**

Heavy Quark Energy Loss, Zero-Rapidity

Lekaveckas, Rajagopal 1311.5577

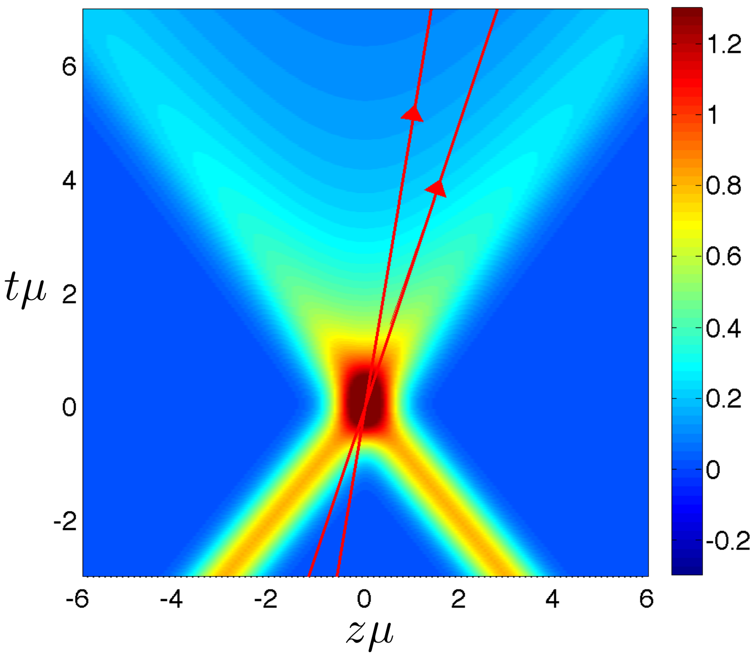


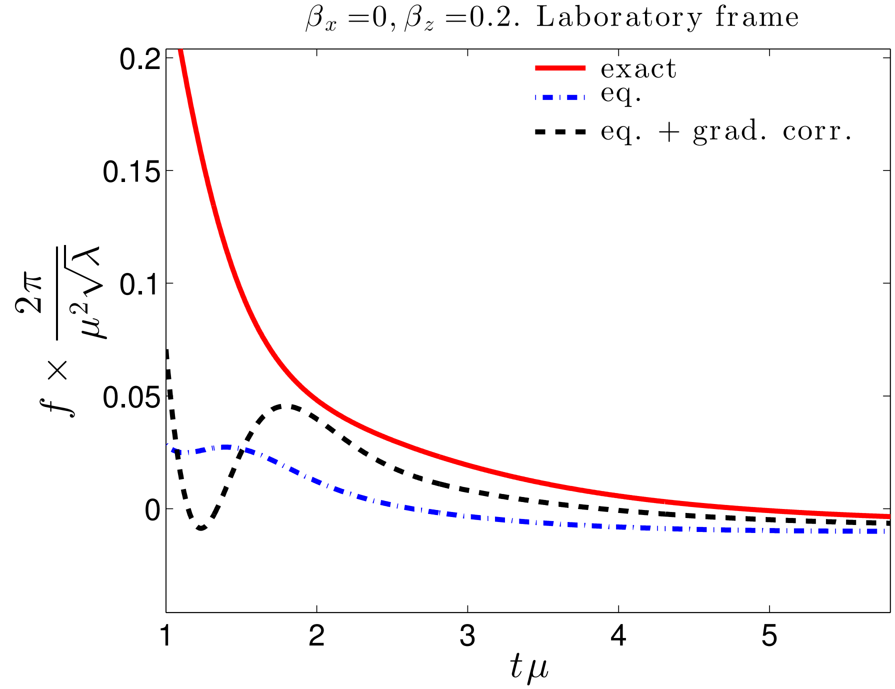


- **Even better for quark with** $\beta_x = 0.5$ **instead of** $\beta_x = 0.95$.
- **The calculation seems to break down if the heavy quark is moving too fast through a changing fluid. Valid for** $b\sqrt{\gamma} \lesssim 1/|\partial_t u^3|$ **and** $b\sqrt{\gamma} \lesssim 1/|\partial_z u^3|$.

Heavy Quark Energy Loss, Nonzero-Rapidity

Lekaveckas, Rajagopal 1311.5577

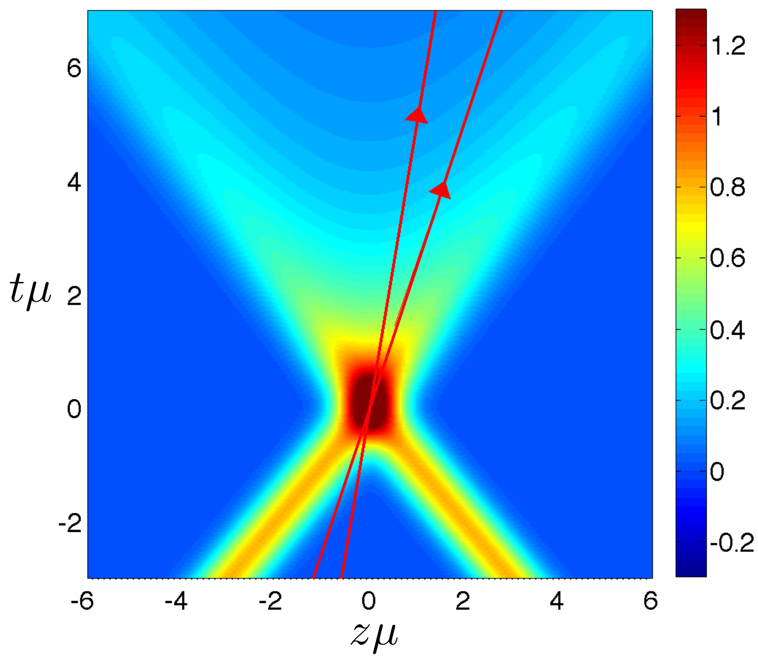


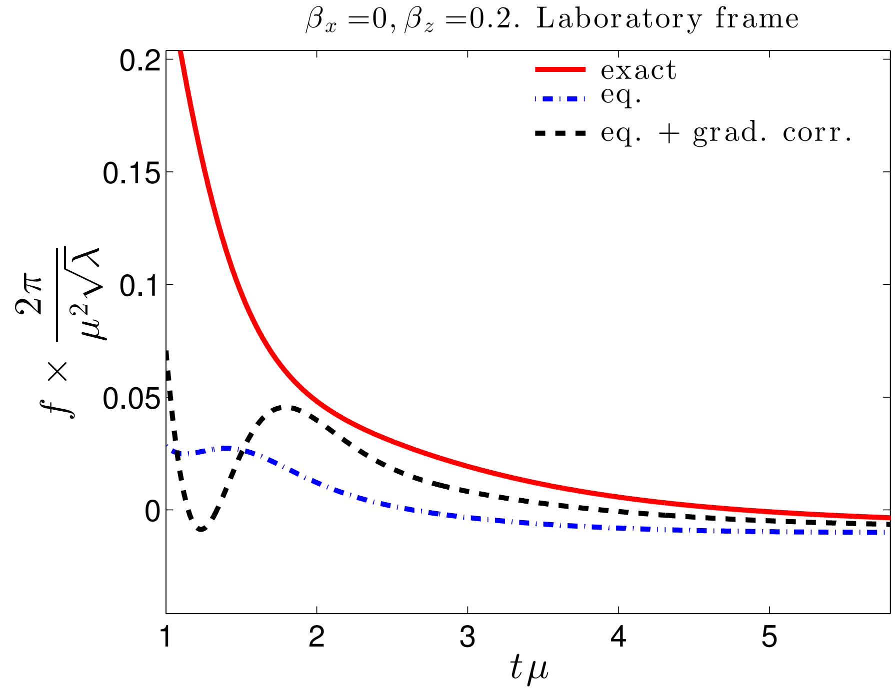


- Here, $\beta_z = 0.2$ and $\beta_x = 0$. Relative velocity of quark and fluid would be zero if expansion were boost invariant. Here, relative velocity, and force, is *small*.
- Absolute magnitude of deviation between first order result and exact result is comparable to what we have seen in other cases.

Heavy Quark Energy Loss, Nonzero-Rapidity

Lekaveckas, Rajagopal 1311.5577

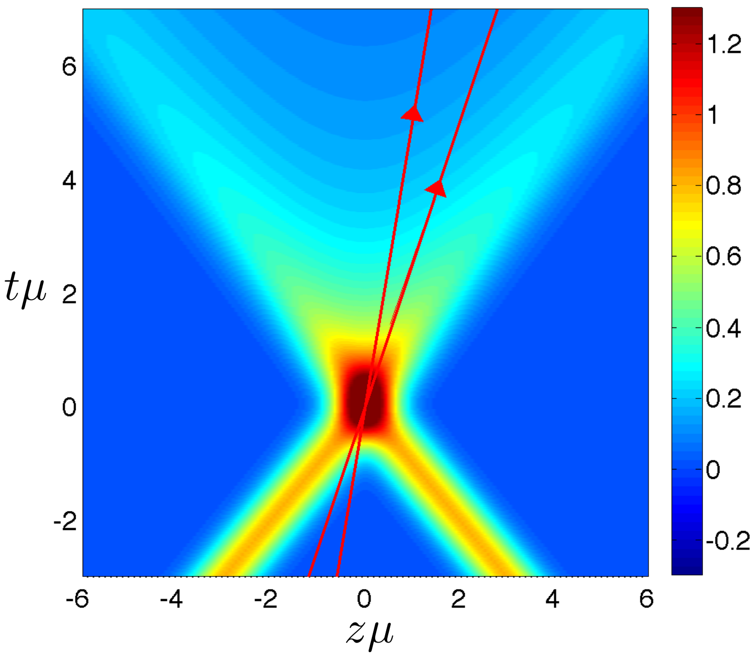


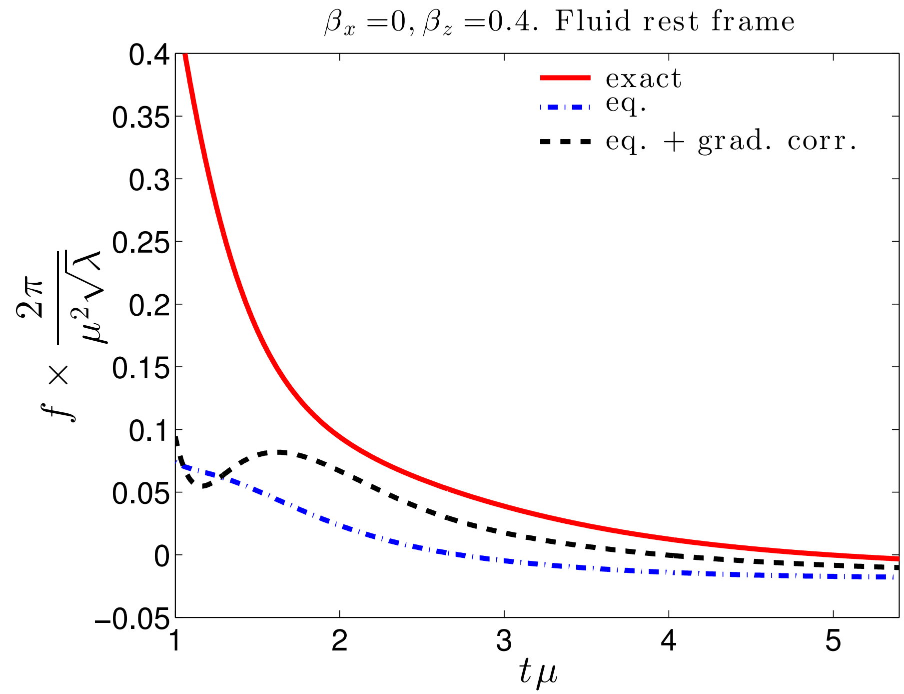


- **Relative velocity, and therefore $f_{(0)}$, flips sign at $t\mu = 2.63$. First order gradients give qualitative explanation of regime where actual 'drag' force hasn't yet flipped, meaning you have to pull the quark in the direction opposite its motion! Drag force exerted by the fluid on the quark is in the direction of its motion! We now see, by analytic calculation, that this is a consequence of the gradients in the fluid.**

Heavy Quark Energy Loss, Nonzero-Rapidity

Lekaveckas, Rajagopal 1311.5577

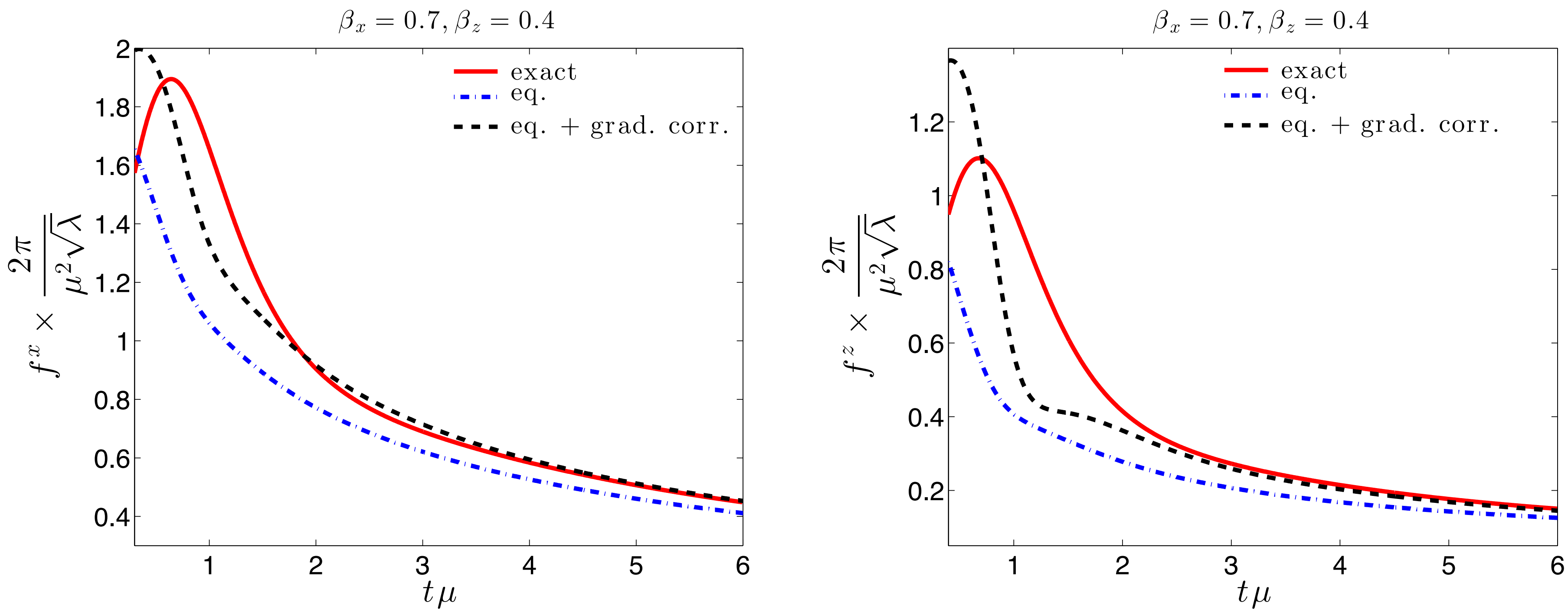




- **Here, $\beta_z = 0.4$ and $\beta_x = 0$. Relative velocity of quark and fluid would be zero if expansion were boost invariant. Here, relative velocity, and force, is *small*. Relative velocity, and therefore $f_{(0)}$, flips sign at $t\mu = 2.73$.**
- **Again, first order gradients explain regime where actual drag force has not yet flipped and so looks backwards.**

Heavy Quark Energy Loss, Nonzero-Rapidity

Lekaveckas, Rajagopal 1311.5577



- **Here, $\beta_z = 0.4$ and $\beta_x = 0.7$. f^x and f^z in the lab frame described well at first order in gradients.**

Heavy Quark Energy Loss, Nonzero-Rapidity

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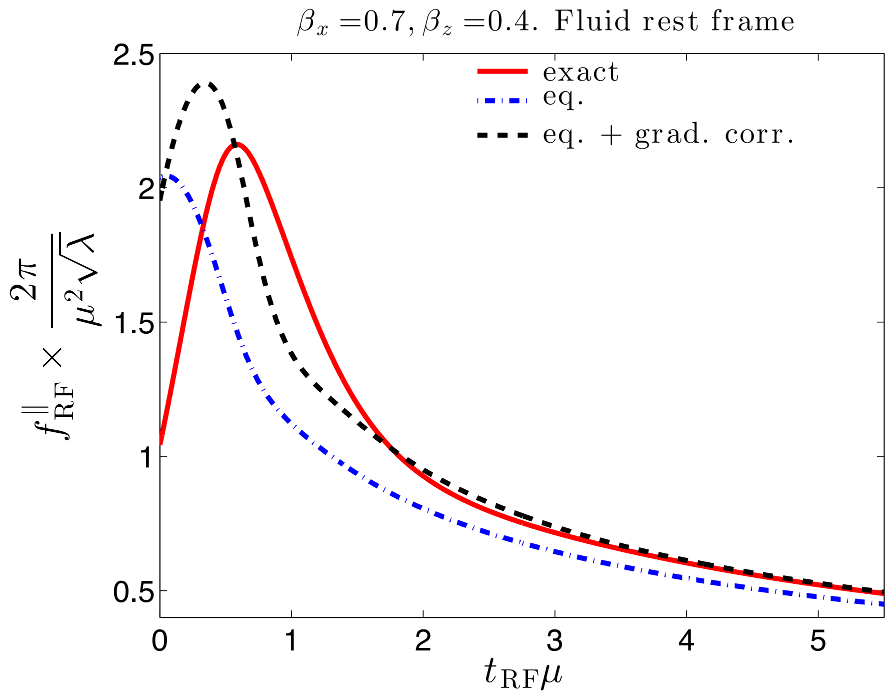
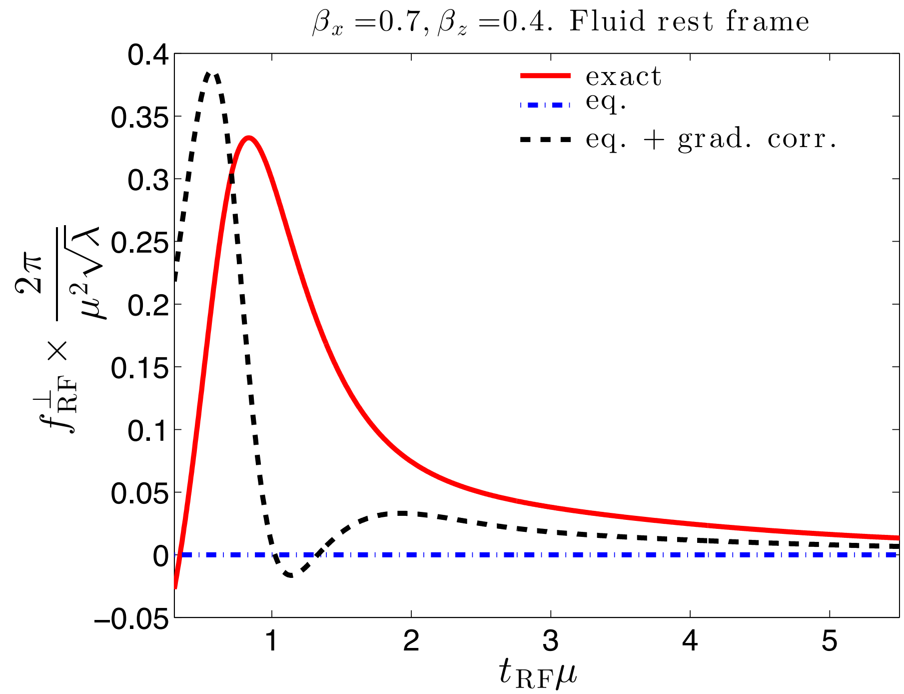




- **Here, $\beta_z = 0.4$ and $\beta_x = 0.7$. $f^{\parallel}$ and $f^{\perp}$, ie parallel and perpendicular to $\vec{\beta}$,** *in the local fluid rest frame.*
- **In the local fluid rest frame, $\vec{f}_{(0)}$ must be parallel to motion of quark. Actual 'drag' force is not: small perpendicular component! This too is explained qualitatively by first order effects of gradients.**

Effects of Fluid Velocity Gradients on Heavy Quark Energy Loss

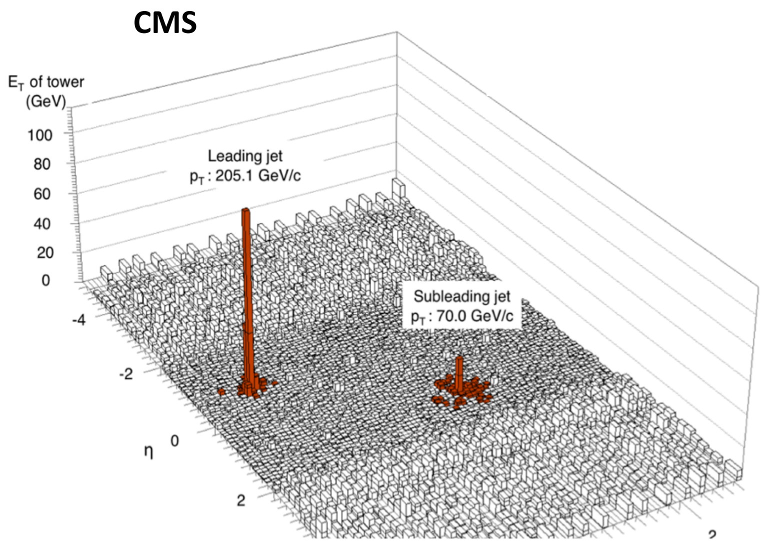
Lekaveckas, Rajagopal, 1311.5577

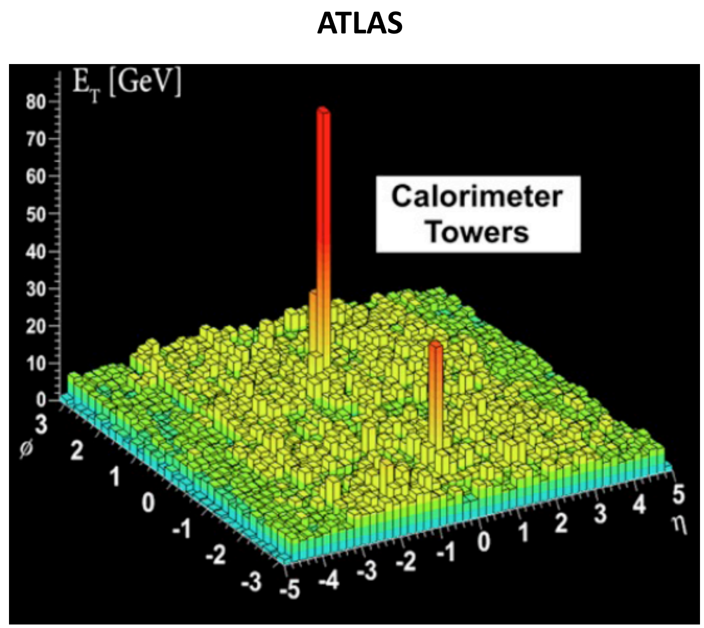
- For heavy quark at zero rapidity, zeroth order result — what the drag force would be in a homogeneous static fluid with the same instantaneous energy density — does a reasonable job, but there is a time delay. Adding corrections that are first order in gradients describes the exact result after hydrodynamization very well.

- For a heavy quark with nonzero rapidity, ie whose velocity has a component in the beam direction, there are small but counterintuitive effects that do not look at all like drag. They are all explained qualitatively by the first order effects of fluid gradients.

- Would be very interesting to try a holographic analysis of the effects of fluid gradients on light quark quenching, or photon emission, or quark-antiquark screening and quarkonium binding.

Jet Quenching, in brief





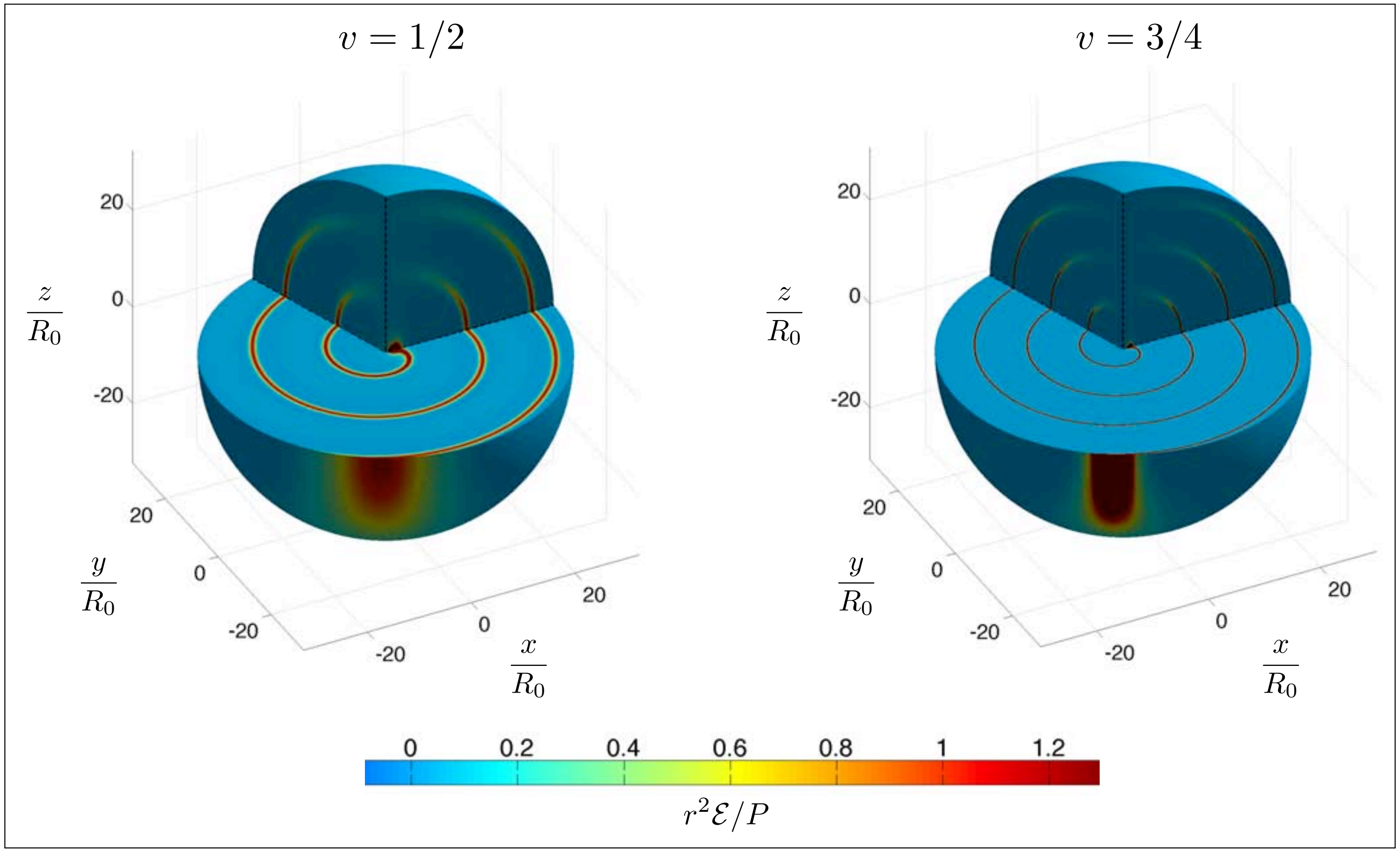
Caricature of jet quenching @ RHIC & LHC:

- 200+ GeV jets lose many tens of GeV passing through the liquid QGP, but jets emerge looking in other respects rather ordinary.
- Lost energy turns into many soft particles at all angles.
- Lower energy jets, seen by ALICE and at RHIC, may emerge surrounded by their debris?

- As if an initially-200-GeV parton/jet in an LHC collision just heats the plasma it passes through, losing significant energy without significant spreading in angle or degradation of its fragmentation function. Are even 200 GeV partons not "seeing" the q+g at short distances?
- One line of theoretical response: more sophisticated analyses of conventional weak-coupling picture of jet quenching. Advancing from parton energy loss and leading hadrons to modification of parton showers and jets.
- We also need strongly coupled approaches to jet quenching, even if just as a foil with which to develop new intuition.
- Problem: jet production is a weakly-coupled phenomenon. There is no way to make jets in the strongly coupled theories with gravity duals.
- But we can make beams of gluons... and 'jets' ...

Synchrotron Radiation in Strongly Coupled Gauge Theories

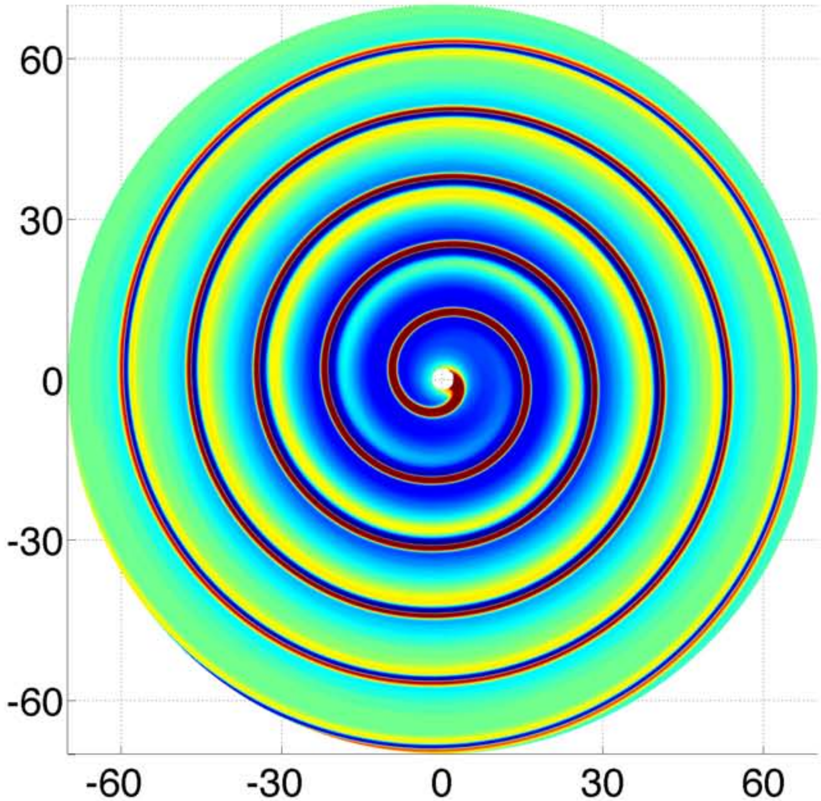
Athanasiou, Chesler, Liu, Nickel, Rajagopal; arXiv:1001.3880

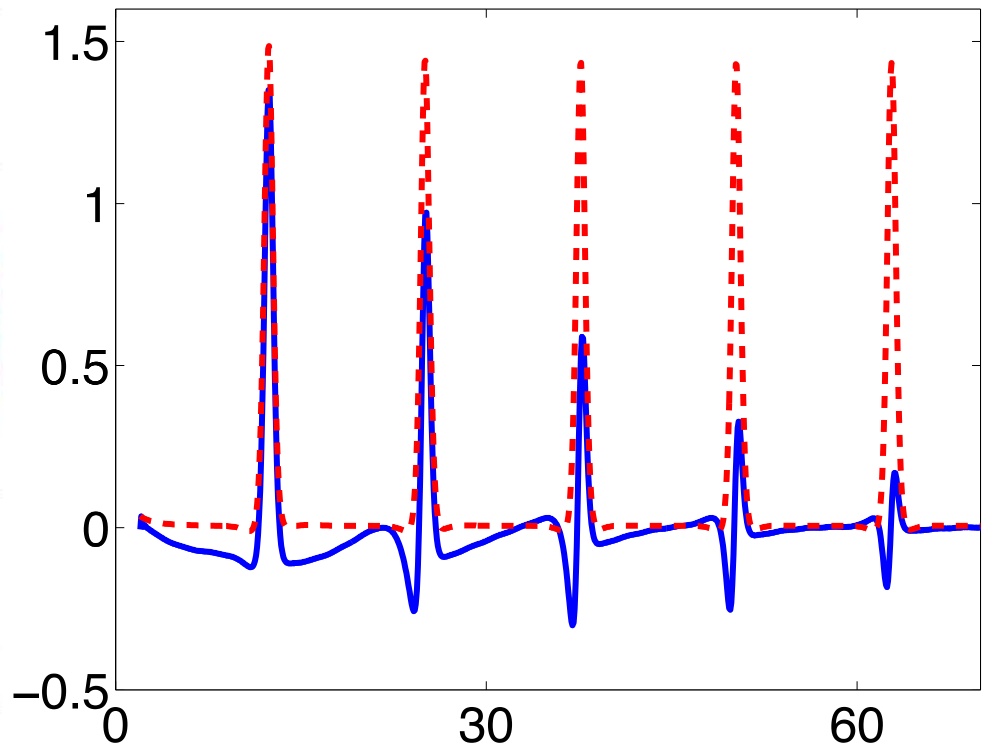


Fully *quantum mechanical* **calculation of gluon radiation from a rotating quark in a** *strongly coupled* **large** N_c *non abelian* **gauge theory, done via gauge/gravity duality. "Lighthouse beam" of synchrotron radiation. Surprisingly similar to classical electrodynamics. Now, shine this beam through strongly coupled plasma...**

Quenching a Beam of Gluons

Chesler, Ho, Rajagopal, arXiv:1111.1691

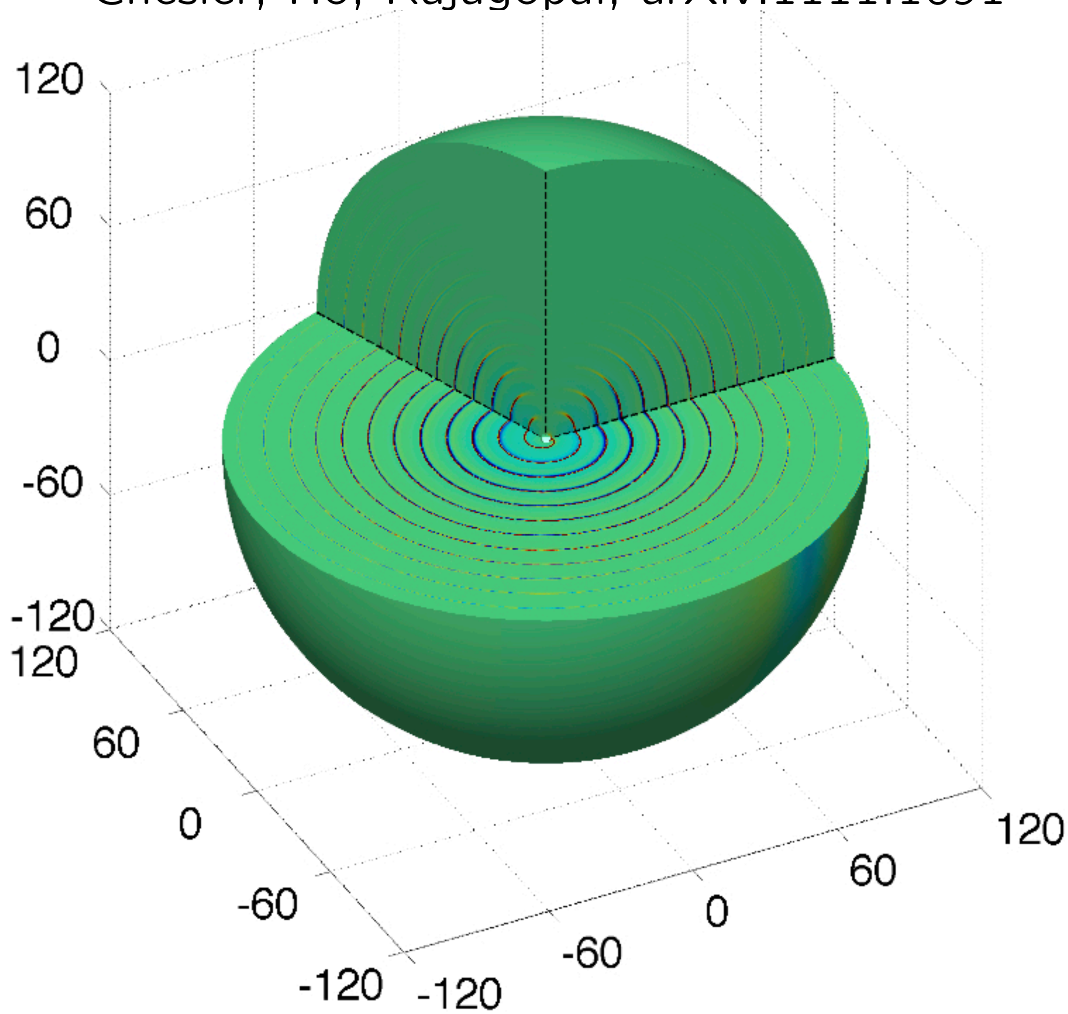




Quark in circular motion makes a beam of gluons that is attenuated dramatically by the plasma, without being significantly broadened — in angle or in momentum distribution.

Quenching a Beam of Gluons

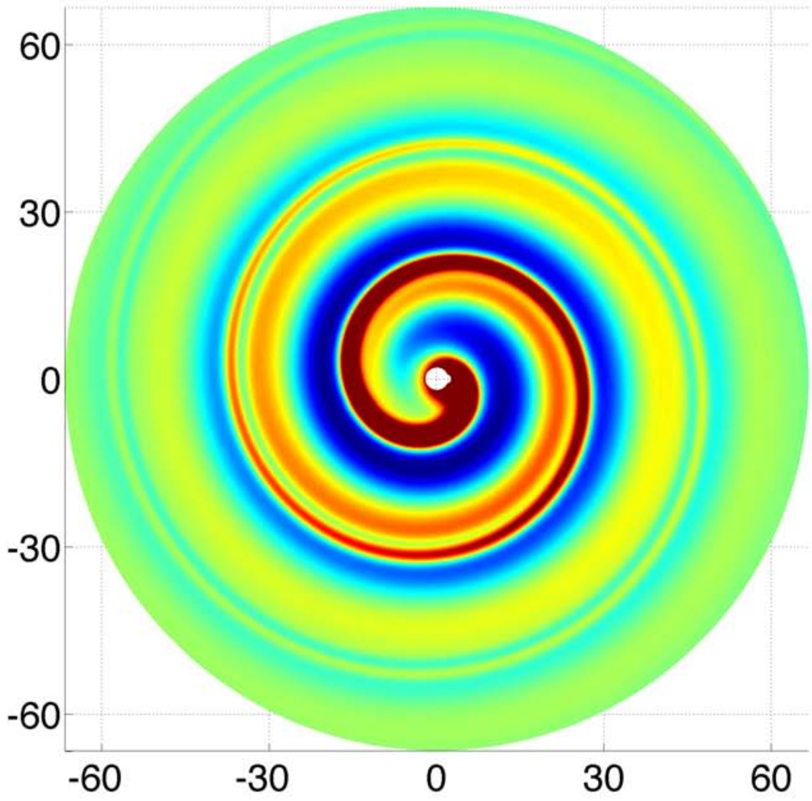
Chesler, Ho, Rajagopal, arXiv:1111.1691

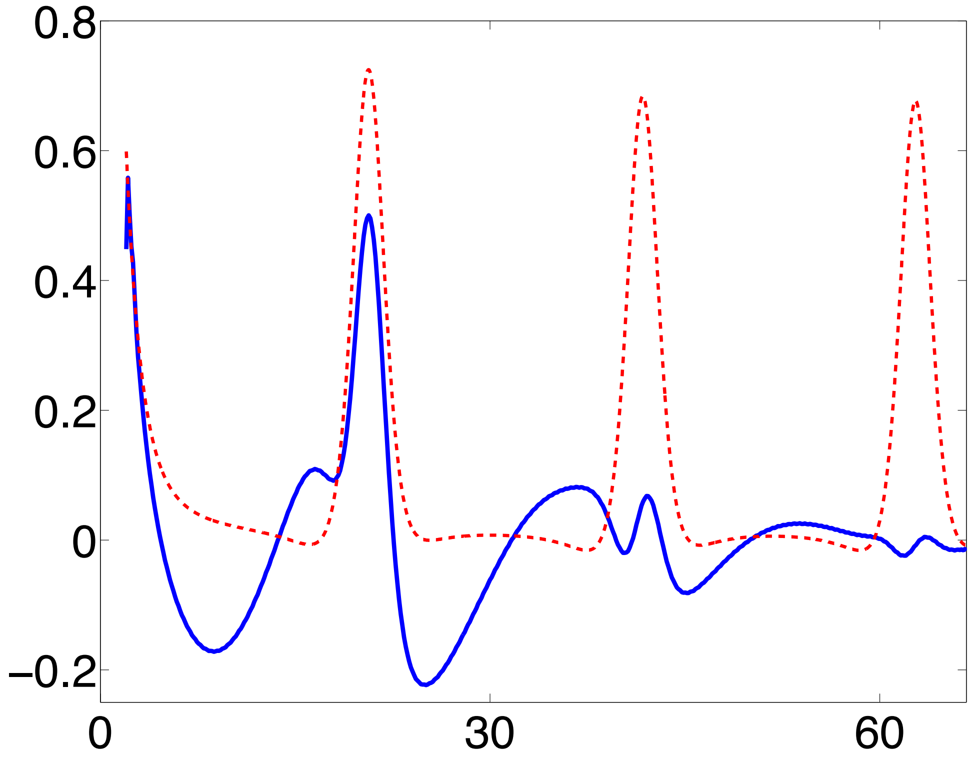


A narrower beam made of higher momentum gluons travels farther, still gets attenuated without spreading in angle or degradation of its momentum distribution.

Quenching a Beam of Gluons

Chesler, Ho, Rajagopal, arXiv:1111.1691





Beam of lower momentum gluons quenched rapidly, and is followed closely by its ‘debris’ — a sound wave.

Quenching a Beam of Gluons

Chesler, Ho, Rajagopal, arXiv:1111.1691

- A beam of gluons with wave vector $q \gg \pi T$ shines through the strongly coupled plasma at close to the speed of light, and is attenuated over a distance $\sim q^{1/3}(\pi T)^{-4/3}$.

- Beam shows no tendency to spread in angle, or shift toward longer wavelengths, even as it is completely attenuated. Like quenching of highest energy jets at LHC?

- Beam sheds a trailing sound wave with wave vector $\sim \pi T$. A beam of higher q gluons travels far enough that it leaves the sound far behind; sound thermalizes. (Highest energy LHC jets?) A beam of not-so-high-q gluons does not go as far, so does get far ahead of its trailing sound wave, which does not have time to thermalize. If it were to emerge from the plasma, it would be followed by its 'lost' energy. (Lower energy jets at RHIC and LHC? Moreso at RHIC since sound thermalizes faster in the higher temperature LHC plasma.)

What happens to the lost energy?

- **Initially, sound waves with wave vector $\sim \pi T$.**
- **The attenuation distance for sound with wave vector q is**

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

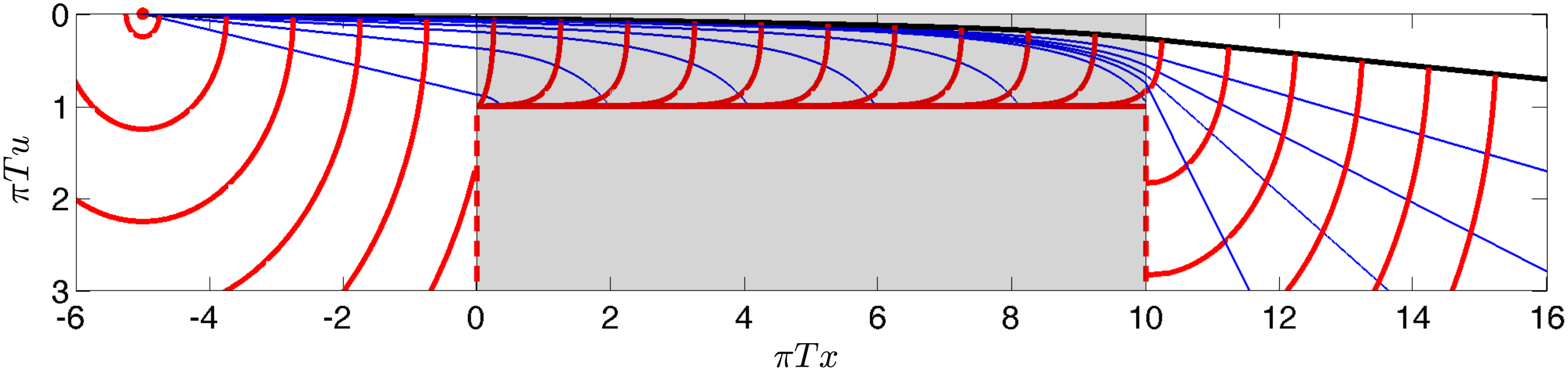
which means that for $q \sim \pi T$ and $v^{\rm sound} \sim 1/\sqrt{3}$ and $\eta/s \sim 2/4\pi$ we have

$$x^{\rm sound}_{\rm damping} \sim 0.6/T \ .$$

- **Energy lost more than a few times $x^{\rm sound}_{\rm damping}$ before the jet emerges will have thermalized, becoming soft particles in random directions. Only the energy lost 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. This should be easier to see for lower energy jets, and in lower temperature plasma.**

Quenching a Light Quark 'Jet'

Chesler, Rajagopal, 1402.6756

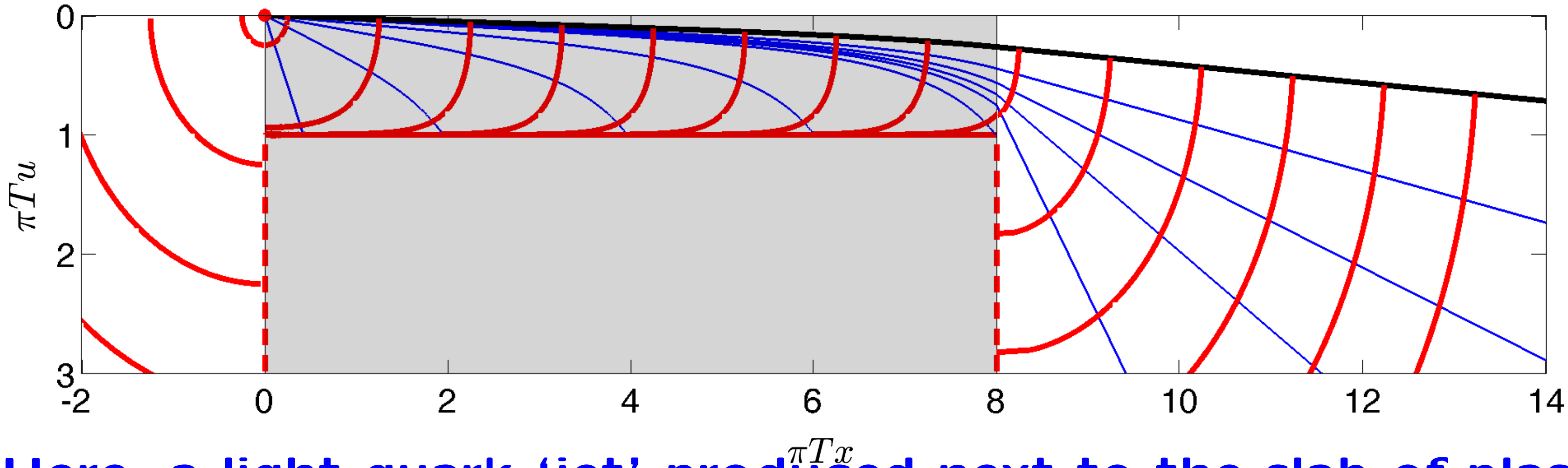


A light quark 'jet', incident with energy E_{in}, shoots through a slab of strongly coupled $\mathcal{N} = 4$ SYM plasma, temperature T, thickness $L\pi T = 10$. What comes out the other side? A 'jet' with $E_{\text{out}} \sim 0.64 E_{\text{in}}$, that looks just like a vacuum 'jet' with that lower energy and a broader opening angle. And, entire calculation of energy loss is geometric!

Two very different holographic approaches, quenching a beam of gluons, quenching a light quark 'jet', give similar conclusions, in qualitative agreement with aspects of what is seen.

Quenching a Light Quark 'Jet'

Chesler, Rajagopal, 1402.6756

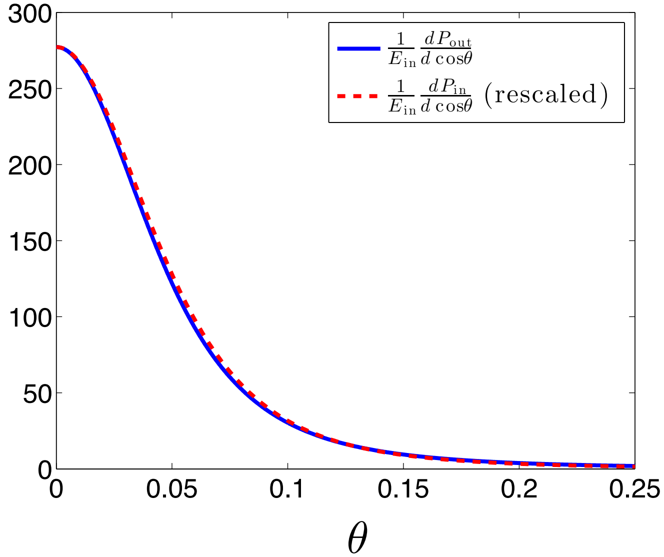


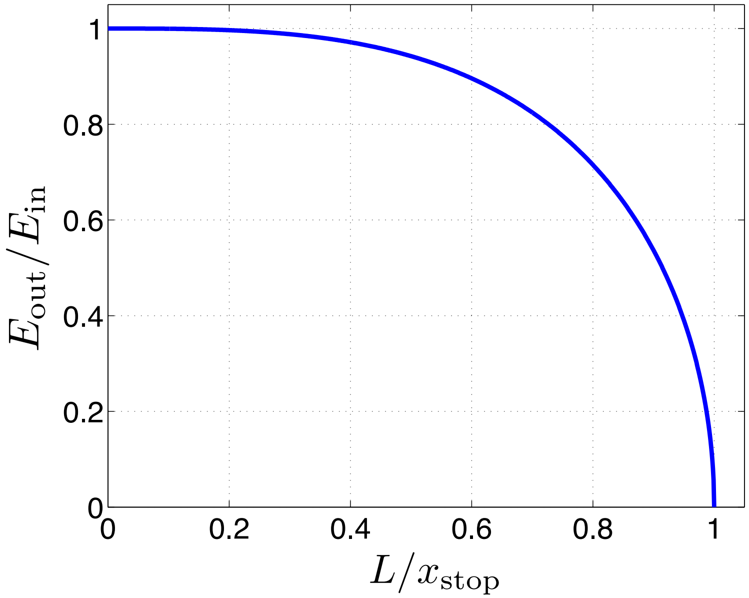
Here, a light quark 'jet' produced next to the slab of plasma with incident energy $E_{\rm in} = 87\sqrt{\lambda}\pi T \sim 87\sqrt{\lambda}$ GeV shoots through the slab and emerges with $E_{\rm out} \sim 66\sqrt{\lambda}$ GeV. Again, the 'jet' that emerges looks like a vacuum 'jet' with that energy.

Geometric understanding of jet quenching, and Bragg peak (maximal energy loss rate as the last energy is lost). Energy propagates along the blue curves, which are null geodesics in the bulk. Opening angle of 'jet' $\leftrightarrow$ downward angle of string endpoint.

Quenching a Light Quark 'Jet'

Chesler, Rajagopal, 1402.6756





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

Geometric derivation of analytic expression for $dE_{\rm out}/dL$ and $E_{\rm out}/E_{\rm in}$ 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 $\pi T x_{\rm stop} \propto (E_{\rm in}/(\sqrt{\lambda}\pi T))^{1/3}$.

A Hybrid Weak+Strong Coupling Approach to Jet Quenching?

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, in progress

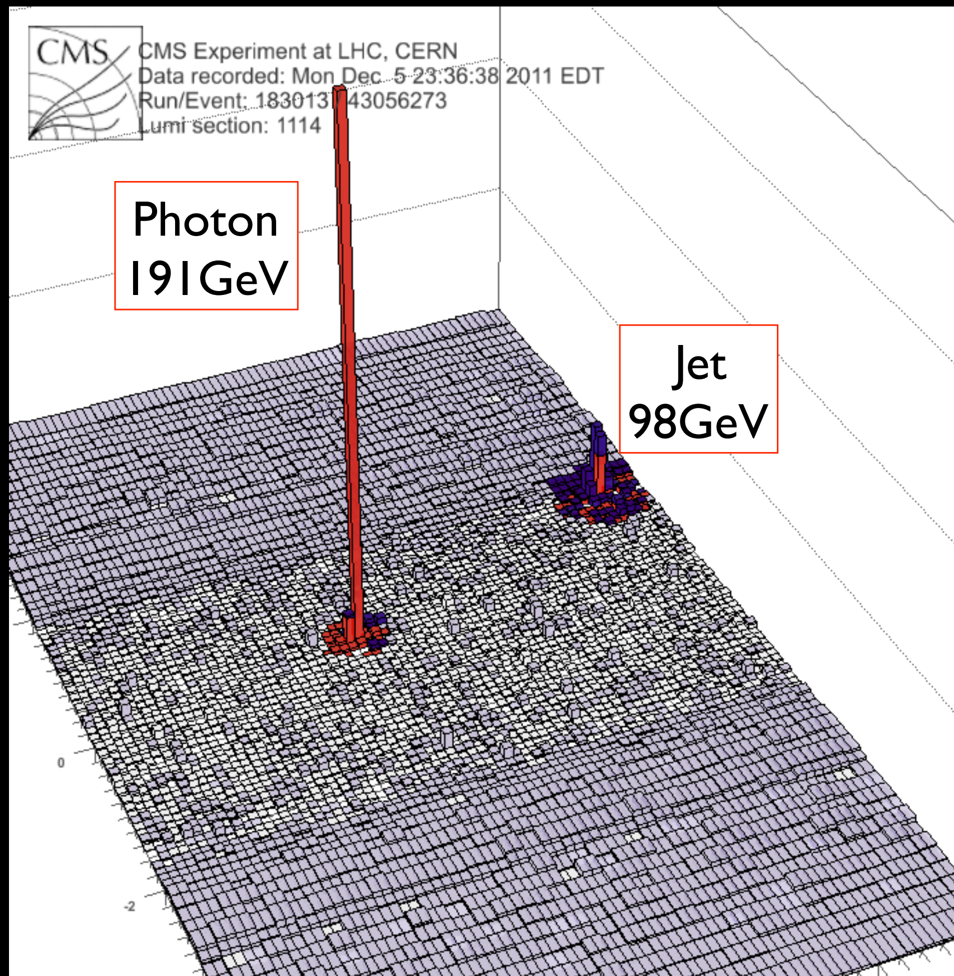
- **Although various holographic approaches at strong coupling capture many qualitative features of jet quenching (e.g. the previous two), it seems quite unlikely that the high-momentum "core" of a quenched LHC jet can be described quantitatively in any strong coupling approach. (Precisely because so similar to jets in vacuum.)**
- **We know that the medium itself is a strongly coupled liquid, with no apparent weakly coupled description. And, the lost energy quickly becomes one with the medium.**
- **A hybrid approach may be worthwhile. Eg make each parton in a parton shower lose energy to "friction", à la light quark in strongly coupled liquid, see previous slide.**
- **We are exploring various different ways of adding "friction" to PYTHIA, looking at R_{AA}, energy loss distribution, dijet asymmetry, jet fragmentation function.**

Weakly Coupled q & g in Liquid QGP

D'Eramo, Lekaveckas, Liu, Rajagopal, 1211.1922

- **We *know* that at a short enough lengthscale, 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 $\sim$ 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.**

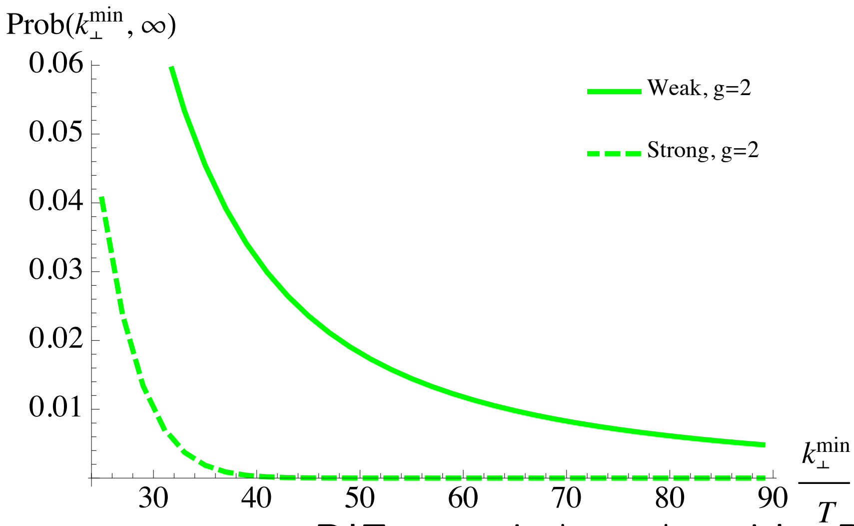
  D'Eramo, Liu, Rajagopal, arXiv:1006.1367

- **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 $k_\perp$.

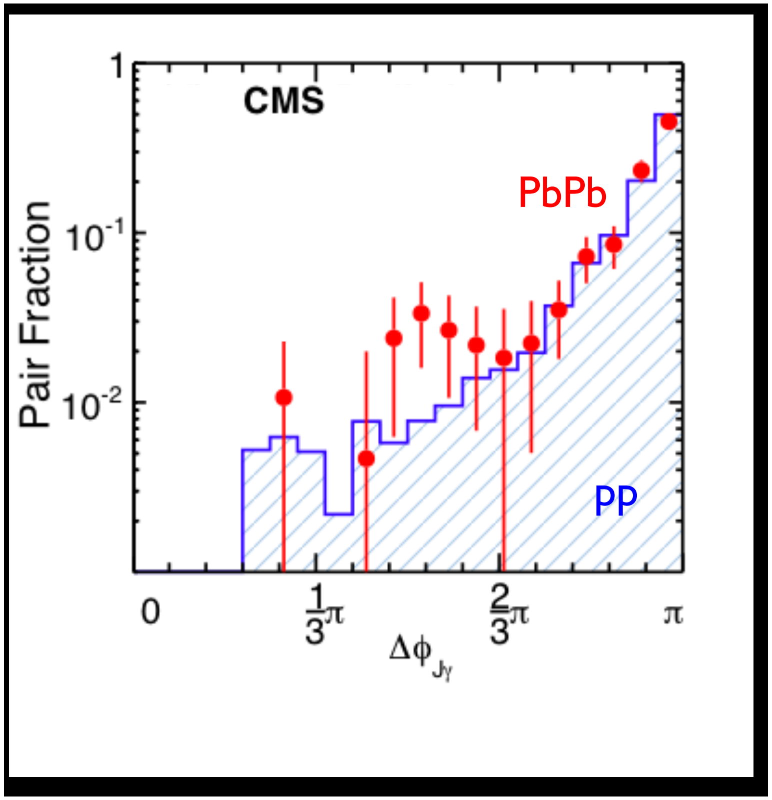
Large deflections rare, but not as rare as if the liquid were a liquid on all scales. They indicate point-like scatterers.



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

- **Probability that a parton that travels $L = 7.5/T$ through the medium picks up $k_\perp > k_{\perp \text{min}}$, for:**
  - **Weakly coupled QCD plasma, in equilibrium, analyzed via SCET+HTL. With $g = 2$, i.e. $\alpha_{\text{QCD}} = 0.32$.**
  - **Strongly coupled $\mathcal{N} = 4$ SYM plasma, in equilibrium, analyzed via holography. With $g = 2$, i.e. $\lambda_{\text{'t Hooft}} = 12$.**
- **Eg for $T = 300$ MeV, $L = 5$ fm, a 60 GeV parton that scatters by 20° picks up $k_\perp = 70\,T$. Prob. $\sim 1\%$ vs. negligible.**
- **Large deflections rare, but not as rare as if the liquid were a liquid on all scales. They indicate point-like scatterers.**

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?

Heavy quarks? Upsilons?

- Heavy quarks are 'tracers', dragged along by and diffusing in the liquid. Diffusion constant tells you about the medium, complementary to η/s. Holographic calculations indicate the heavy quarks should 'go with the flow'.
- If very energetic heavy quarks interact with strongly coupled plasma as holographic calculations indicate, which is to say like a bullet moving through water, b and c quark energy loss is same for quarks with same *velocity*. Quite different than weakly coupled expectations, where both γ and M matter. Want to study b and c quark energy loss vs. momentum. Data on identified b and c quarks coming soon, at RHIC via upgrades being completed.
- Upsilons probe plasma on different length scales. 1S state is very small. 3S state is the size of an ordinary hadron. They "melt" (due to screening of $b - \bar{b}$ attraction) at different, momentum-dependent (cf holographic calculations), temperatures. This story is just beginning. Stay tuned.

HOW TO CALCULATE PROPERTIES OF STRONGLY COUPLED QGP LIQUID?

① LATTICE QCD
- perfect for THERMODYNAMICS (ie static properties)
- calculation of η, and other transport coefficients, beginning
- jet quenching and other dynamic properties not in sight

② PERTURBATIVE QCD
- right theory but wrong approximation

③ Calculate QGP properties in other theories that are analyzable at strong coupling.
- Are some dynamical properties universal? I.e. same for strongly coupled plasmas in a large class of theories. What properties? What class of theories?

AdS/CFT

We now know of infinite classes of different gauge theories whose quark-gluon plasmas:

- are all equivalent to string theories in higher dimensional spacetimes that contain a black hole
- all have

$$\frac{\varepsilon}{T^4} = \frac{3}{4}\left(\frac{\varepsilon}{T^4}\right)_0$$

Gubser Klebanov Tseytlin Peet....

$$\eta/s = \frac{1}{4\pi}$$

Son Policastro Starinets Kovtun Buchel Liu ....

in the limit of strong coupling and large number of colors.

[Not known whether QCD in this class.]

$\mathcal{N}=4$ Supersymmetric Yang Mills

- A gauge theory specified by two parameters: N_c and $g^2 N_c \equiv \lambda$.
- Conformal. (λ does not run.)
- If we choose λ large, at $T \neq 0$ we have a strongly coupled plasma.
- This 3+1 dimensional gauge theory is equivalent to a particular string theory in a particular spacetime: $\underbrace{AdS_5}_{4+1 \text{ "big" dimensions}} \times \underbrace{S_5}_{5 \text{ "curled up" dim.}}$
- In the $N_c \to \infty$, $\lambda \to \infty$ limit, the string theory reduces to classical gravity. ∴ Calculations easy at strong coupling.

AdS / CFT

Maldacena; Witten; Gubser Klebanov Polyakov; ....

N=4 SYM is equivalent to Type IIB String theory on $\underbrace{AdS_5}_{\text{4+1 "big" dimensions}} \times \underbrace{S_5}_{\text{5 curled up dimension}}$

Translation Dictionary:

N=4 SYM gauge theory in 3+1 dim	String theory in 4+1(+5) dim

$$\frac{g^2 N_c}{4\pi N_c} = g_{string}$$

⌈$N_c \to \infty$ at fixed $g^2 N_c$ means $g_{string} \to 0$⌋

$$\sqrt{g^2 N_c} = R^2/\alpha'$$

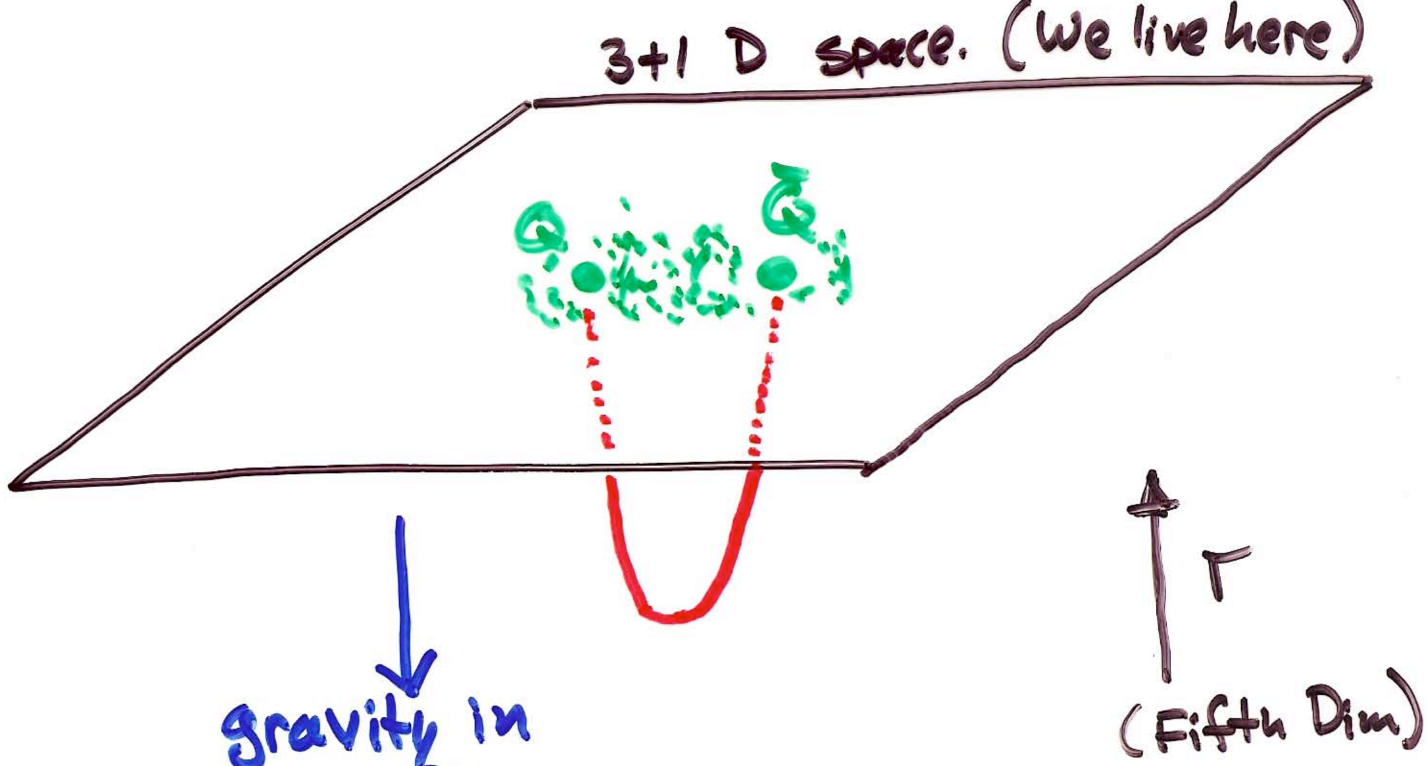
⌈R: AdS curvature

$\frac{1}{2\pi\alpha'}$: string tension⌋

Heat the gauge theory to a temperature T. $= T_H = r_0/\pi R^2$ Add a Black hole in the 5th dimension, with

⌈r_0: location of BH horizon in fifth dim.⌋

How can strings in 5D describe, say, force between Q and $\bar{Q}$ in a 4D gauge theory?

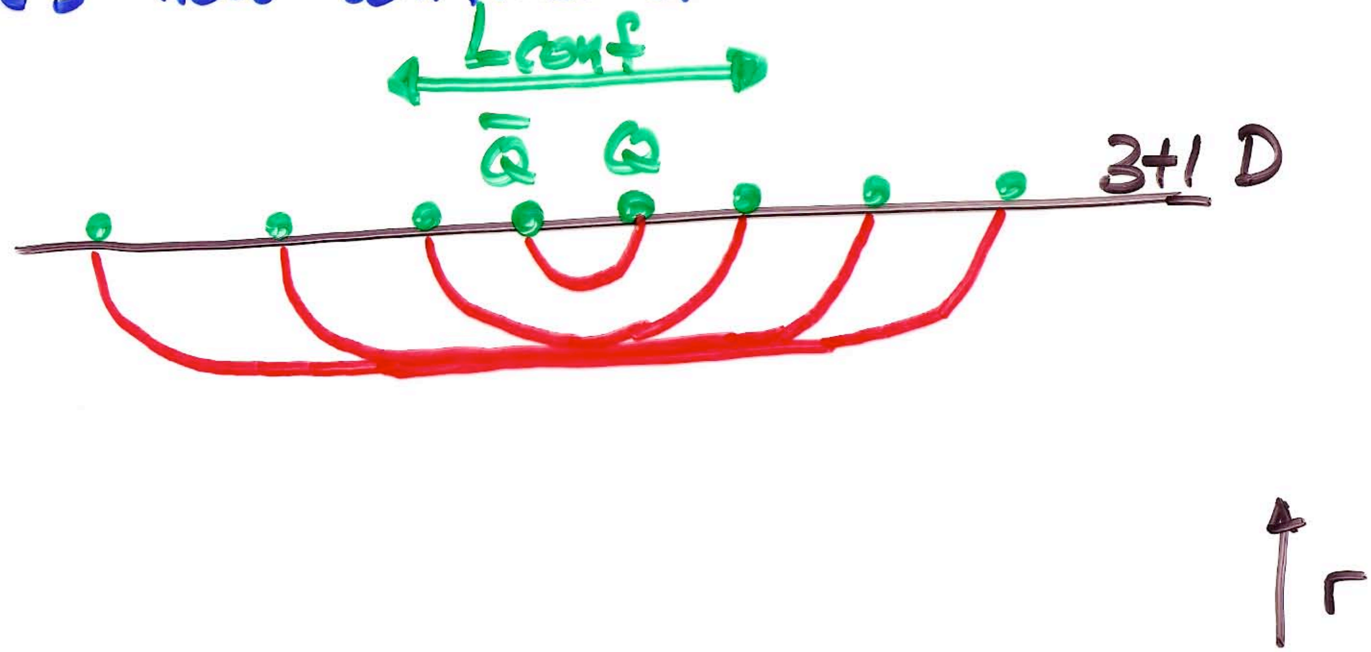


(AdS is a curved space)

- Extremize energy of U string. (Like catenary problem, in unusual gravitational field.)
  - Large $g^2 N_c$ → Large tension → no fluctuation
  - Large N_c → Small g_{string} → no loops break off.
- Force between Q and $\bar{Q}$ $= \frac{d}{d\ \text{separation}}$ (Energy of string)

CONFINEMENT?

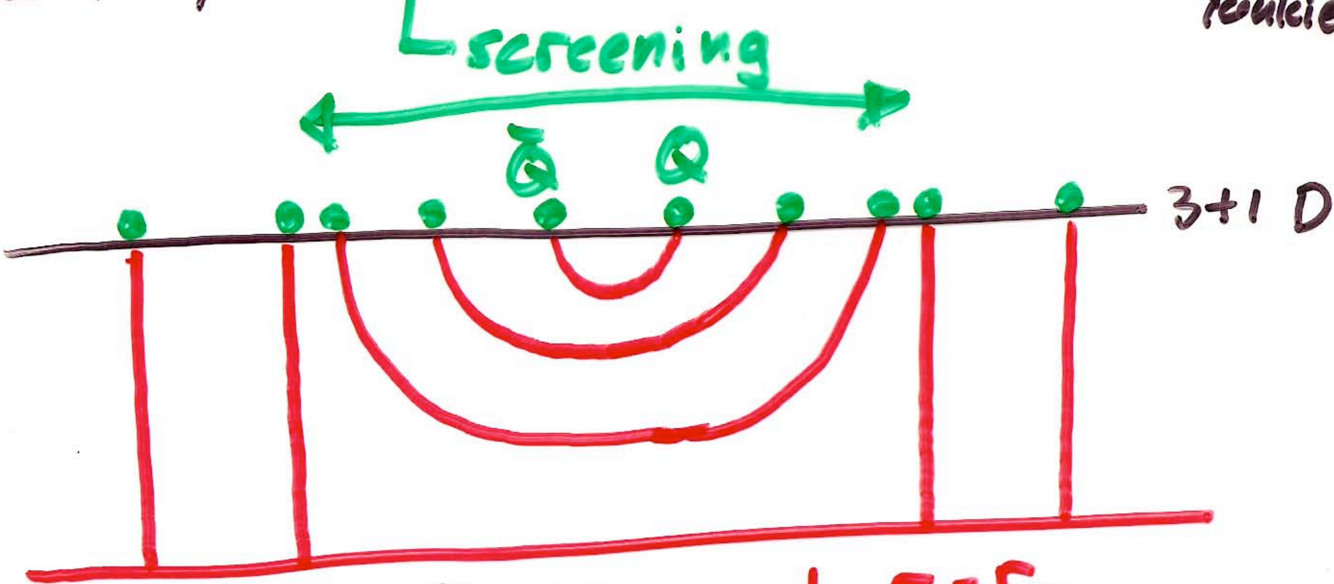
Here's how confinement can arise ....



- This does <u>not</u> happen in $N=4$
  - shape of string stays same as L increases. ($N=4$ is conformal)
- Confining gauge theories with dual descriptions like this <u>are</u> known.
- QCD not known to have a description like this.
- Don't use $N=4$ as a guide to QCD at $T=0$.

DECONFINEMENT AT $T \neq 0$

Maldacena; Rey Yee; Rey Theisen Yee; Brandhuber Itzhaki Sonnenschein Yankielowicz



Black Hole Horizon at $r = r_0$

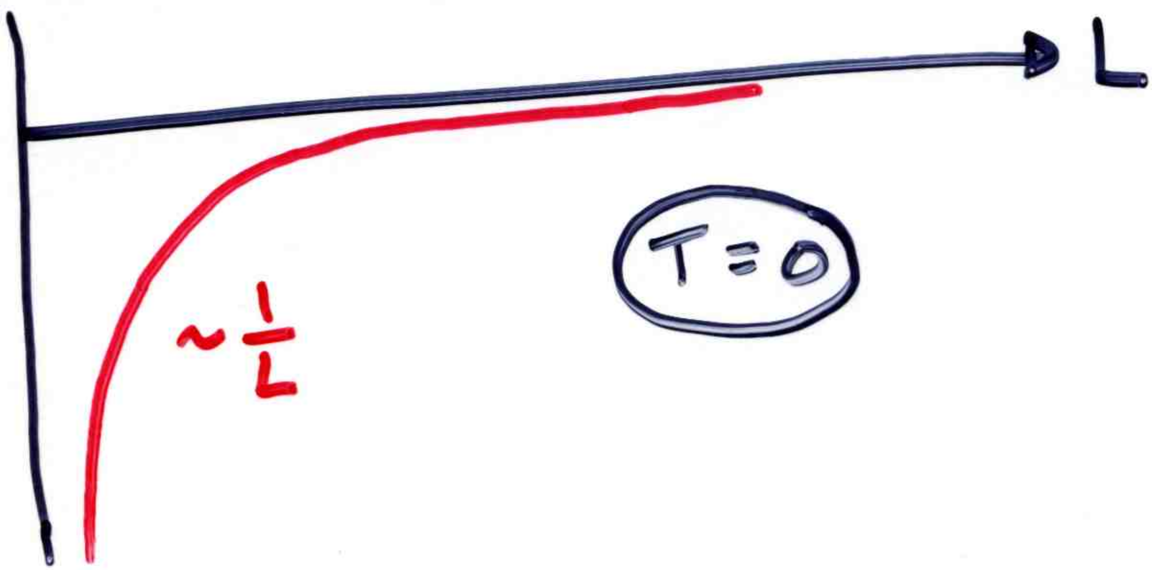
- For $L < L_s$, force between Q & $\bar{Q}$.
- For $L > L_s$, force is screened. Q & $\bar{Q}$ deconfined.
- In $N=4$ SUSY QCD,

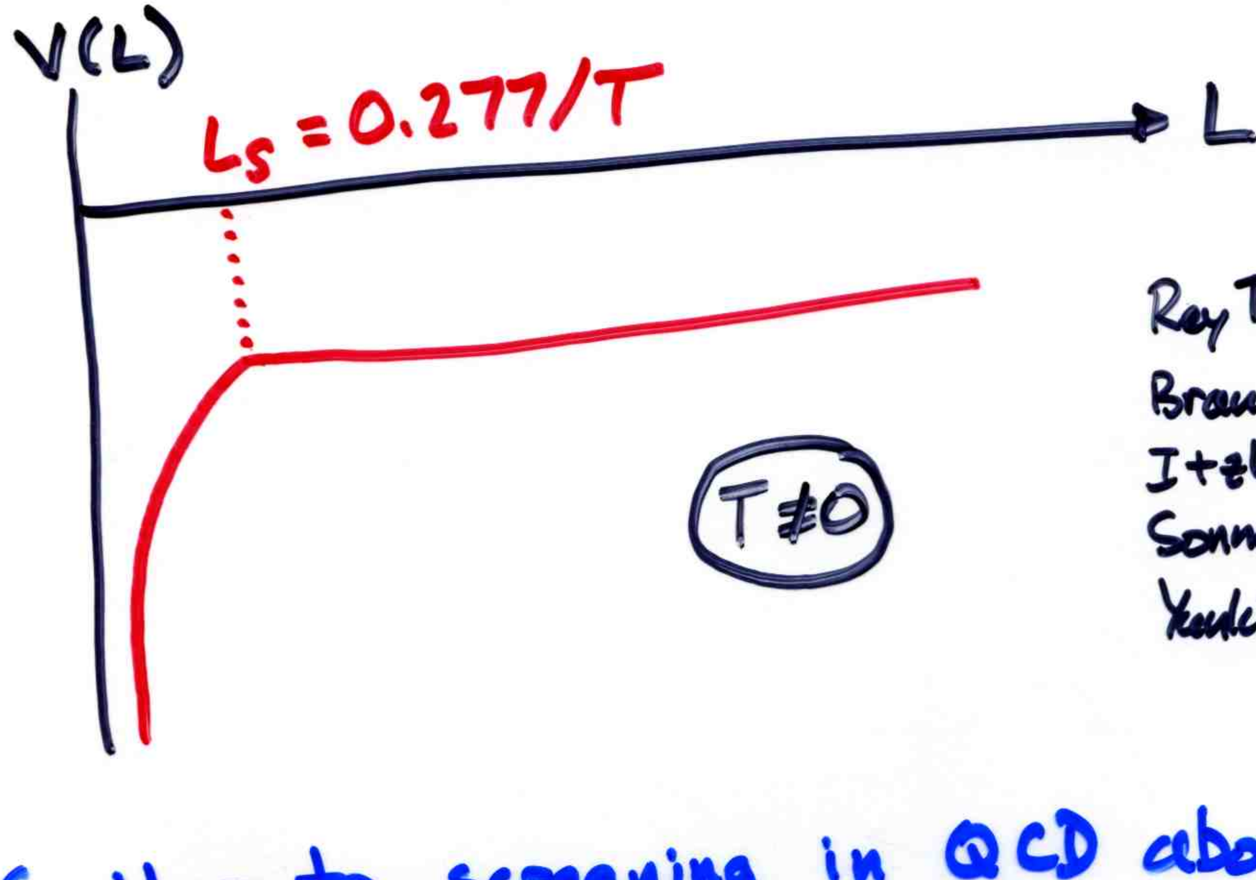
$$L_s = \frac{0.277}{T}$$

- In QCD, force between <u>static</u> Q & $\bar{Q}$ in QGP <u>can</u> be calculated. (Lattice QCD) Can define L_s, though it is not a sharp boundary. Find: $L_s \sim \frac{0.5}{T} \rightarrow \frac{0.7}{T}$ Kaczmarek Karsch Zantow Petreczky
- $N=4$ gets this feature of the QCD strongly interacting QGP to within factor of 2!

SCREENING IN N=4

$V(L)$ = potential between static Q & $\bar{Q}$

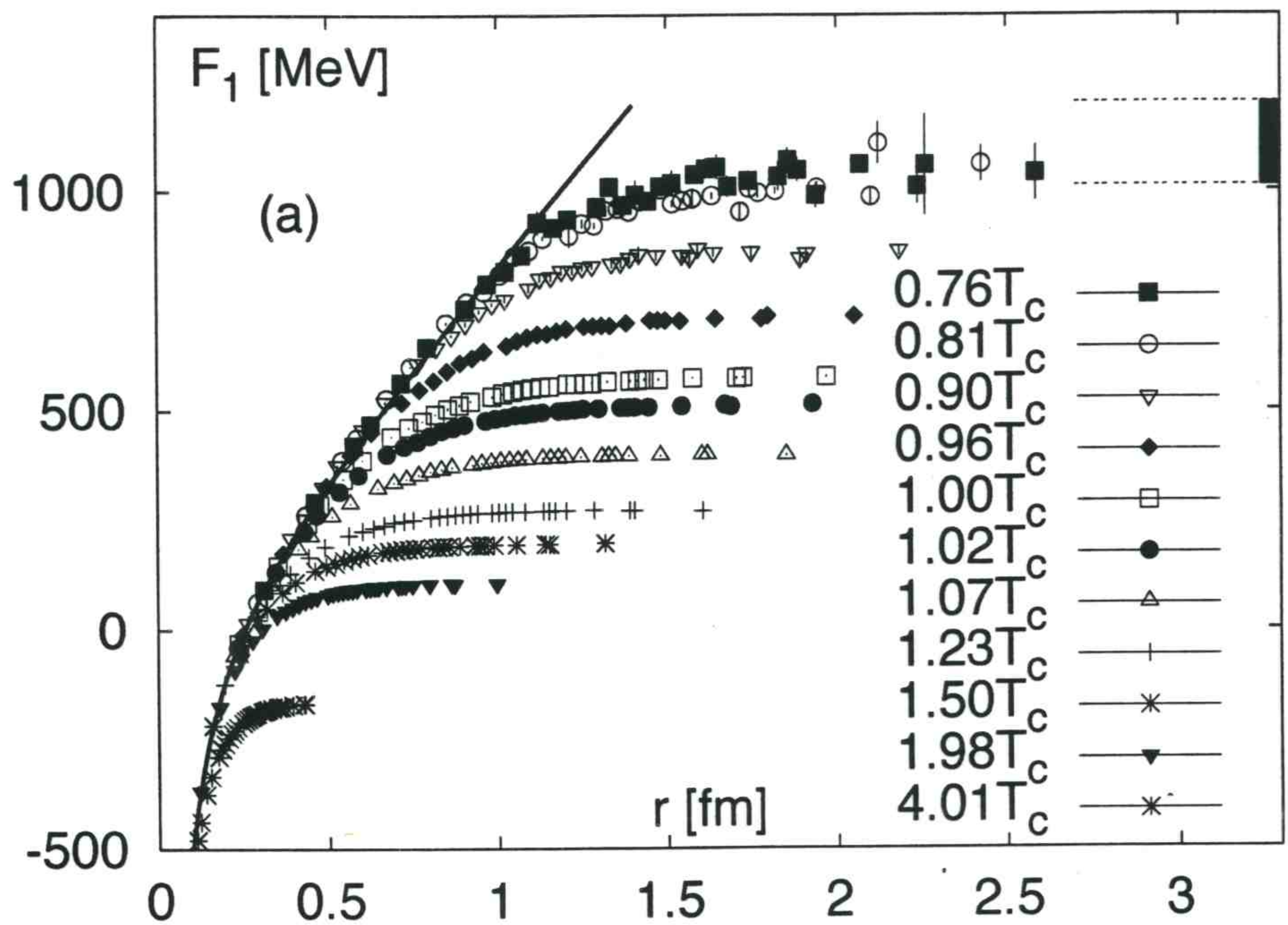




Rey Theisen Yee;
Brandhuber
Itzhaki
Sonnenschein
Yankielowicz

Similar to screening in QCD above QCD's Tc....

SCREENING IN QCD



Kaczmarek, Zantow

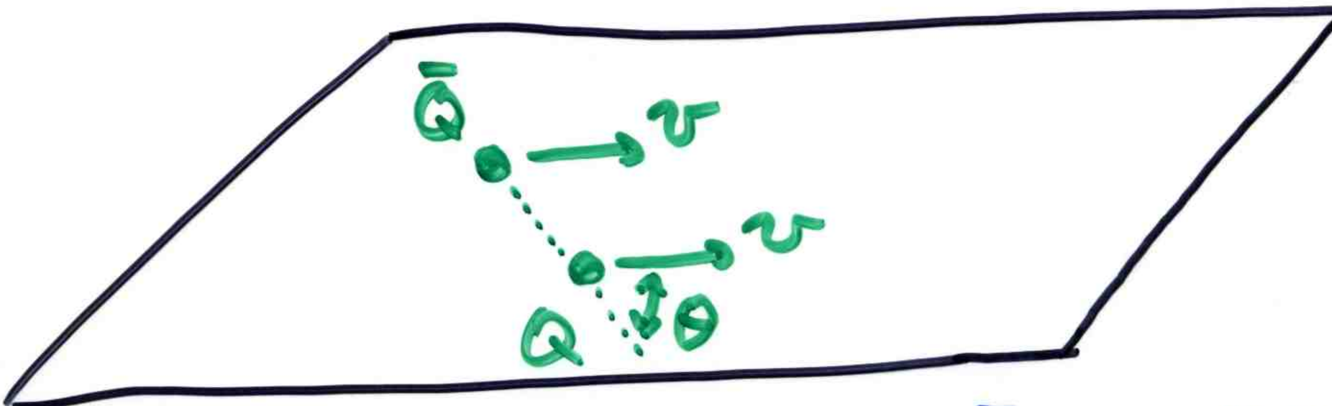
lattice QCD calculation

[Unquenched. $N_f = 2$]

Upon defining an L_s, the authors find $L_s \sim 0.5/T$

A PREDICTION FOR EXPERIMENT

H. Liu, KR, Wiedemann



- Calculate force between $Q + \bar{Q}$ moving through the N=4 QGP. (Not known how to do this calculation in QCD.) Find:

$$L_s = \frac{f(v,\theta)}{\pi T}(1-v^2)^{1/4}$$

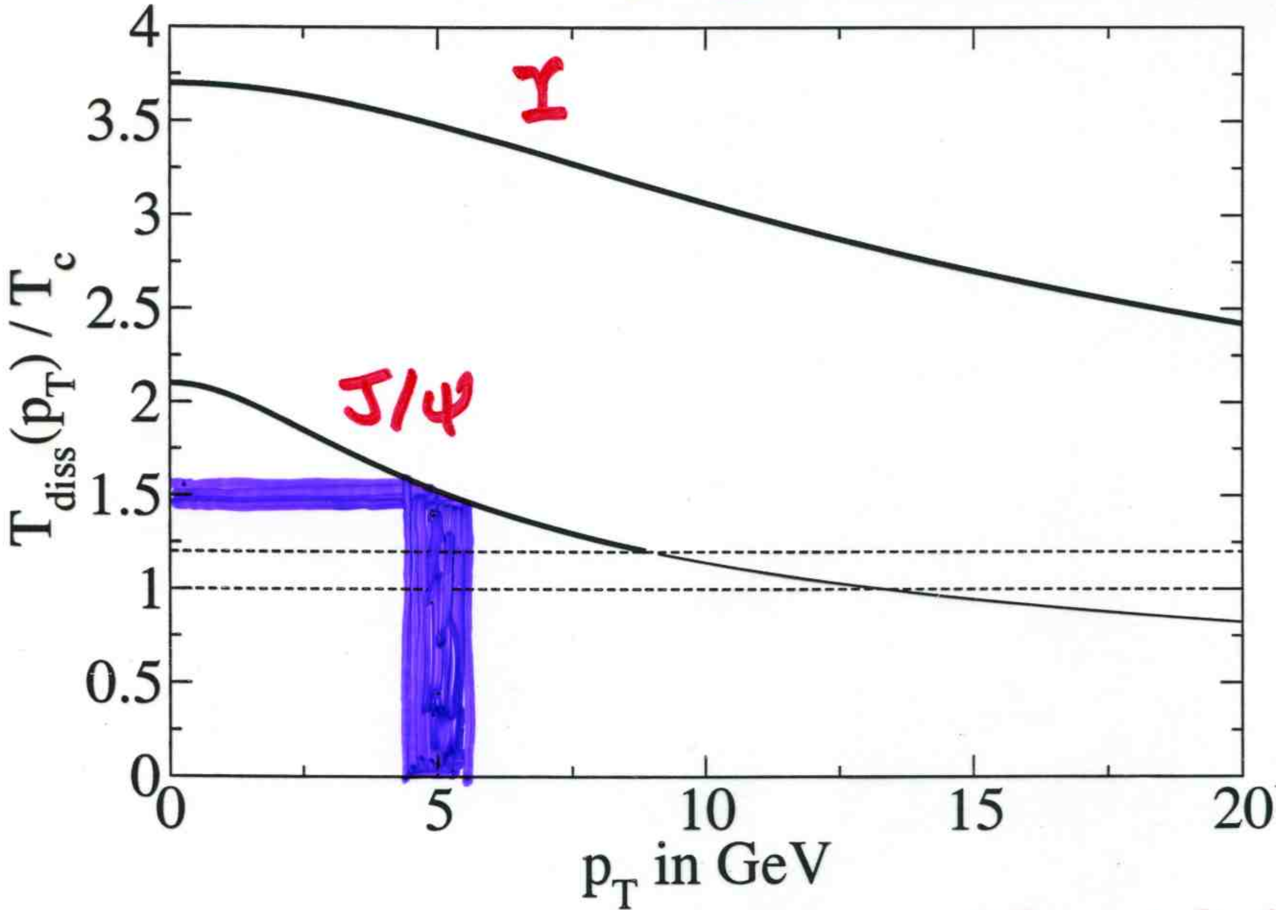
LRW; Peeters et al; Chernicoff et al; Caceres et al

where f is almost a constant. ($f(0,0) = 0.869$; $f(1, \frac{\pi}{2}) = .743$)

- So, $L_s(v,T) \simeq L_s(0,T)/\sqrt{\gamma}$
- Makes sense if L_s controlled by ε, since $\varepsilon \sim T^4$ and $\varepsilon(v) = \varepsilon(0)\gamma^2$.
- J/ψ ($\bar{c}c$) and Υ ($\bar{b}b$) mesons dissociate when T reaches T_{diss}, at which $L_s \sim$ meson size.
- Suggests: $T_{diss}(v) \sim T_{diss}(0)/\sqrt{\gamma}$!

$T_{dissociation}$ vs. P_T

- At $P_T = 0$, $T_{diss}^{J/\psi} \simeq 2.1\, T_c$, from lattice QCD
- Υ curve schematic. (Scaled rel. to J/ψ by meson size in vacuum.)



- Our velocity scaling: $T_{diss}(v) \simeq T_{diss}(0)/\sqrt{\gamma}$

+ Karsch Kharzeev Satz model (ie $2.1\, T_c < T_{RHIC} < 1.2\, T_c$)

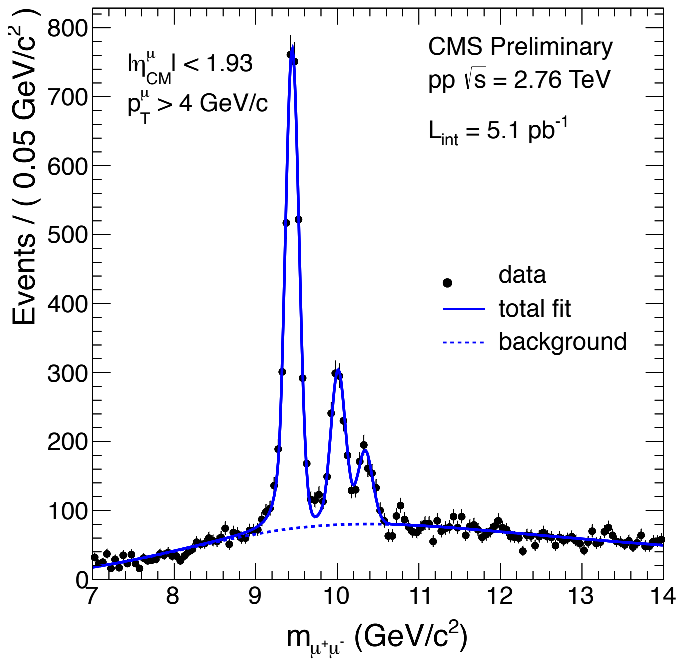
⇒ J/ψ <u>themselves</u> dissociate for

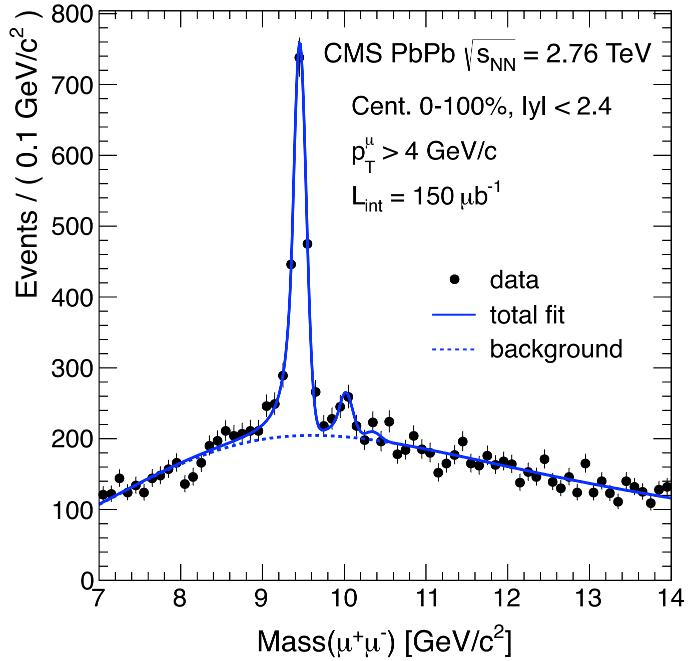
$P_T > 5\,\text{GeV}$ if $T_{RHIC} \sim 1.5\, T_c$

$P_T > 9\,\text{GeV}$ if $T_{RHIC} \sim 1.2\, T_c$

Upsilon 2S Suppression in PbPb

CMS 1208.2826 and CMS-HIN-13-003





- **Sequential suppression of Υ states in PbPb: No sign of Υ(3S). Υ(2S) substantially suppressed.**
- **It will be very interesting to see how the right-hand plot changes for higher p_T Υs. As you increase p_T, expect Υ(2S) to go the way of the Υ(3S). And then, in principal, above some rather high p_T the Υ(1S) also.**

A Grand Challenge

- How can we clarify the understanding of fluids without quasiparticles, whose nature is a central mystery in so many areas of science?
- We are developing more, and better, ways of studying the properties and dynamics of Liquid QGP — "our" example of a fluid without quasiparticles.
- At some short length scale, a weakly coupled picture of the QGP as made of quarks and gluons must be valid, even though on its natural length scales it is a strongly coupled fluid. It will be a challenge to see and understand *how* the liquid QGP emerges from short-distance quark and gluon quasiparticles.
- Holographic calculations have yielded, and are yielding, many qualitative insights that are helping advance the ongoing campaigns on both these fronts.

Gauge/String Duality, Hot QCD and Heavy Ion Collisions

Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann

A 500 page book. We finished the manuscript a few months ago. To appear circa May 2014, Cambridge University Press.

95 page intro to heavy ion collisions and to hot QCD, including on the lattice. 70 page intro to string theory and gauge/string duality. Including a 'duality toolkit'.

280 pages on 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.

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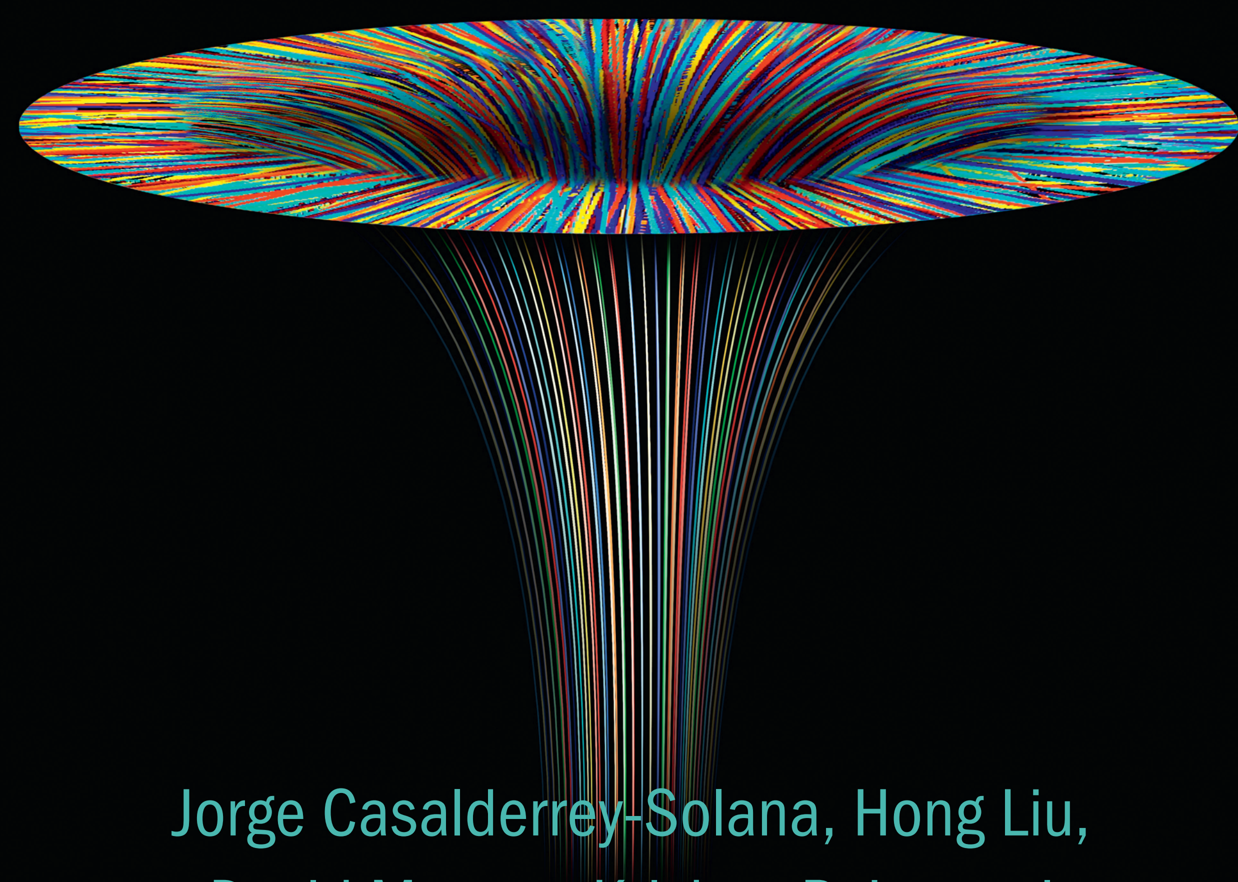

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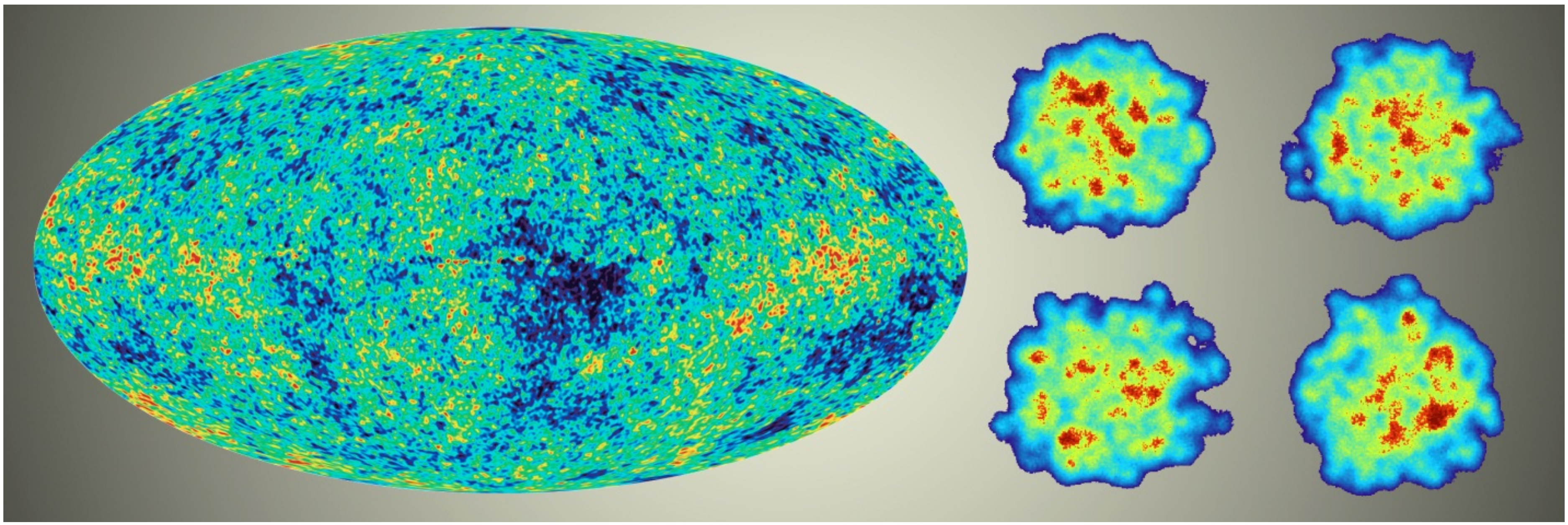
QGP cf CMB



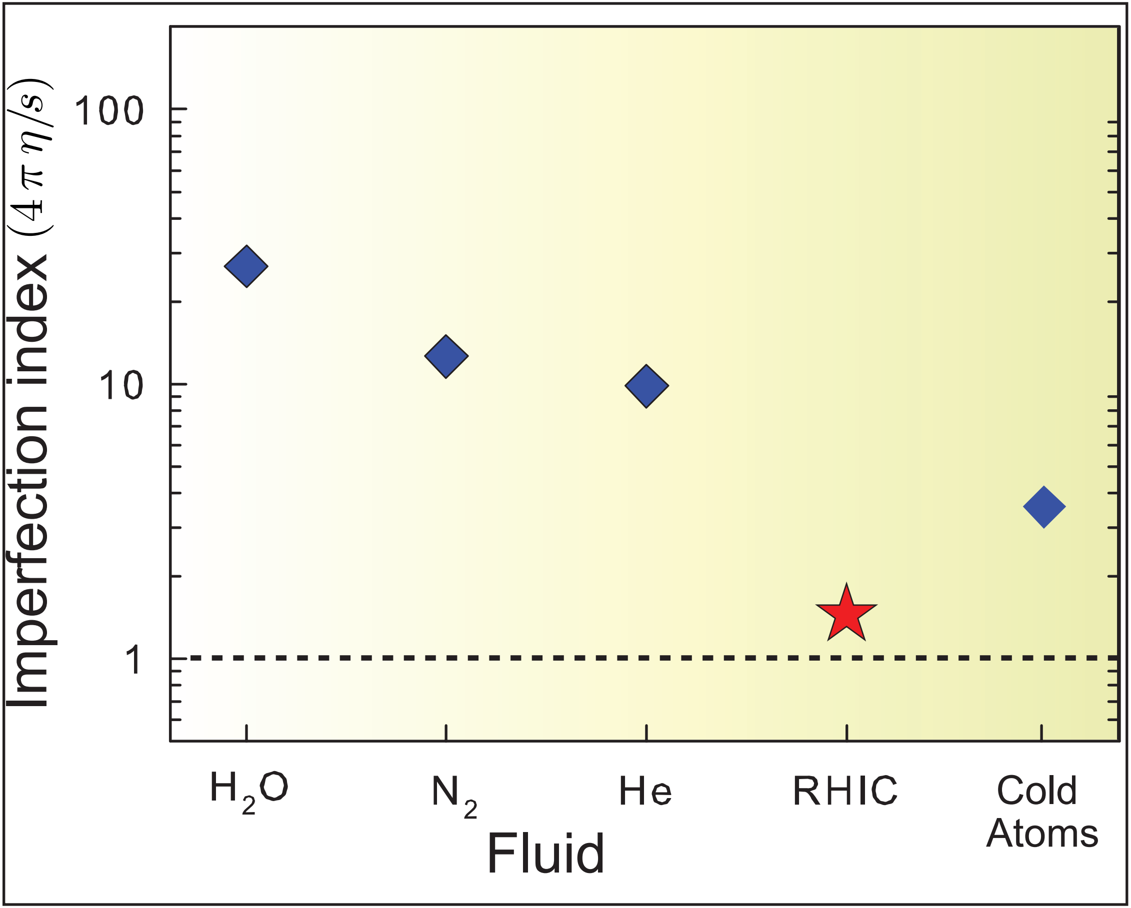
QGP cf CMB

- In cosmology, initial-state quantum fluctuations, processed by hydrodynamics, appear in data as c_ℓ's. From the c_ℓ's, learn about initial fluctuations, and about the "fluid" — eg its baryon content.

- In heavy ion collisions, initial state quantum fluctuations, processed by hydrodynamics, appear in data as v_n's. From v_n's, learn about initial fluctuations, and about the QGP — eg its η/s, ultimately its $\eta/s(T)$ and ζ/s.

- Cosmologists have a huge advantage in resolution: c_ℓ's up to $\ell \sim$ thousands. But, they have only one "event"!

- Heavy ion collisions only up to v_6 at present. But they have billions of events. And, they can do controlled variations of the initial conditions, to understand systematics...


Imperfection index $(4\pi\eta/s)$
100
10
1
H2O
N2
He
RHIC
Cold Atoms
Fluid