Theory

Overview

Krishna Rajagopal

MIT

Quark Matter 2011; Annecy, France; May 23, 2011

One Theorist's

View....

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Liquid Quark-Gluon Plasma: Opportunities and Challenges

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A Grand Opportunity

- By colliding nuclei at enormous energies, two extraordinary accelerators — RHIC and now the LHC — are making little droplets of “big bang matter”: the same stuff that filled the whole universe for the first few microseconds after the big bang.

- Using five extraordinary detectors, 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.

Liquid Quark-Gluon Plasma

- Hydrodynamic analyses of RHIC data on how asymmetric blobs of Quark-Gluon Plasma expand (explode) 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.

- Can we make quantitative statements, with reliable error bars, about η/s?

- Does the story change at the LHC?

Determining η/s from RHIC data

- **Using relativistic viscous hydrodynamics to describe expanding QGP, microscopic transport to describe late-time hadronic rescattering, and using RHIC data on pion and proton spectra and v_2 as functions of p_T and impact parameter...**

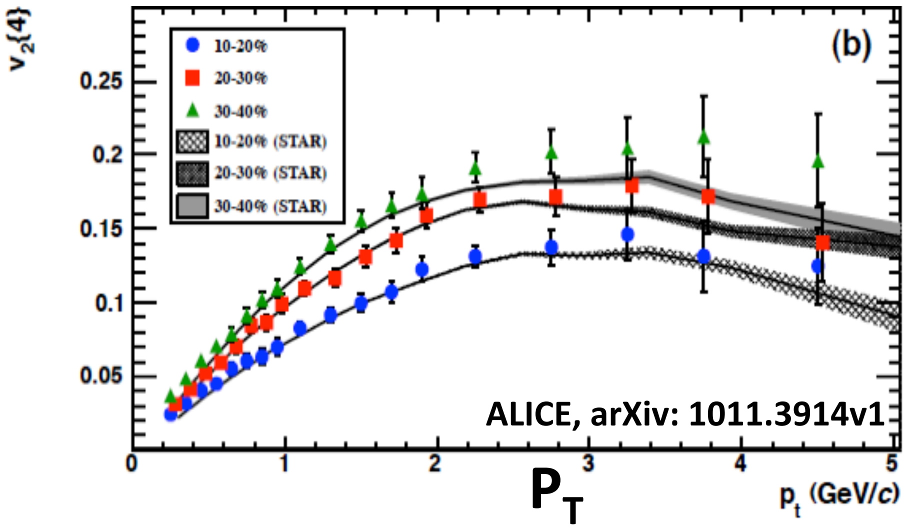
- **QGP@RHIC, with $T_c < T \lesssim 2T_c$, has $1 < 4\pi\eta/s < 2.5$. Uncertainty was more than twice as large at QM09. Largest remaining uncertainty: initial conditions.**

- **$4\pi\eta/s \sim 10^4$ for typical terrestrial gases, and 10 to 100 for all known terrestrial liquids except one. Hydrodynamics works much better for QGP@RHIC than for water.**

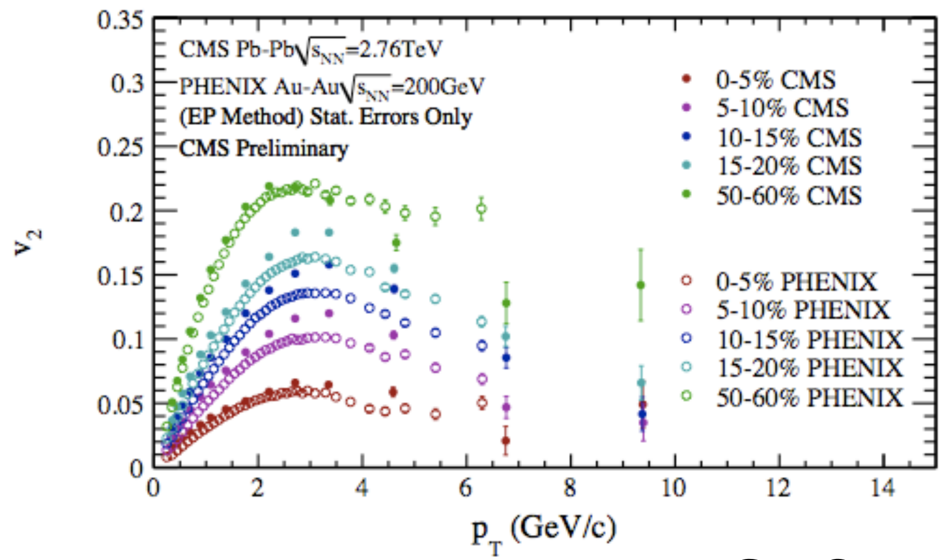
- **$4\pi\eta/s = 1$ for any (of the by now very many) known strongly coupled gauge theory plasmas that are the "hologram" of a (4+1)-dimensional gravitational theory "heated by" a (3+1)-dimensional black-hole horizon.**

Song, Bass, Heinz, Hirano, Shen arXiv:1101.4638

What changes at the LHC?



ALICE

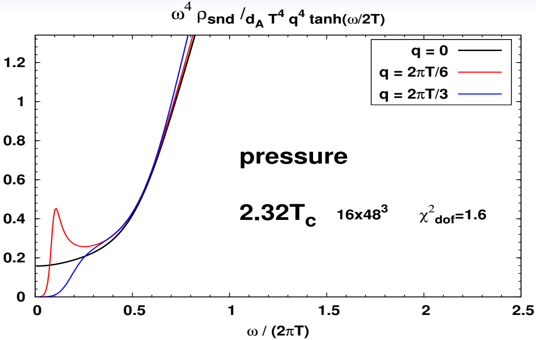


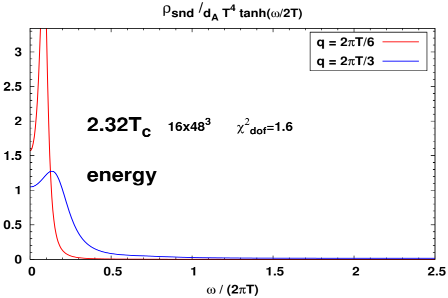
CMS

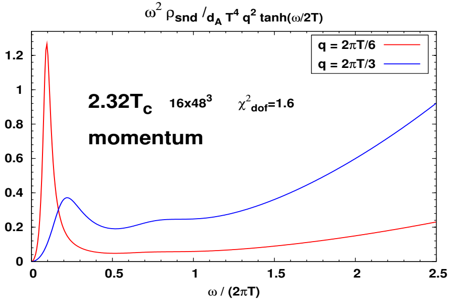
$v_2(p_T)$ **for charged hadrons similar at LHC and RHIC. These data will be much discussed at QM11. At zeroth order, no apparent evidence for any change in** η/s**. The hotter QGP at the LHC is still a strongly coupled liquid.**

Sound spectral functions for Gluon Plasma on lattice [H. Meyer, QM 09]

- 16×48^3 lattice
- 48 data pts; 7 fit params
- momenta up to $q = \pi T$
- $[\eta/s]_{GP,lat} = 0.20(3)$ at $1.58T_c$
- $[\eta/s]_{GP,lat} = 0.26(3)$ at $2.32T_c$
- No large change in η/s from RHIC to LHC expected







Rapid Equilibration?

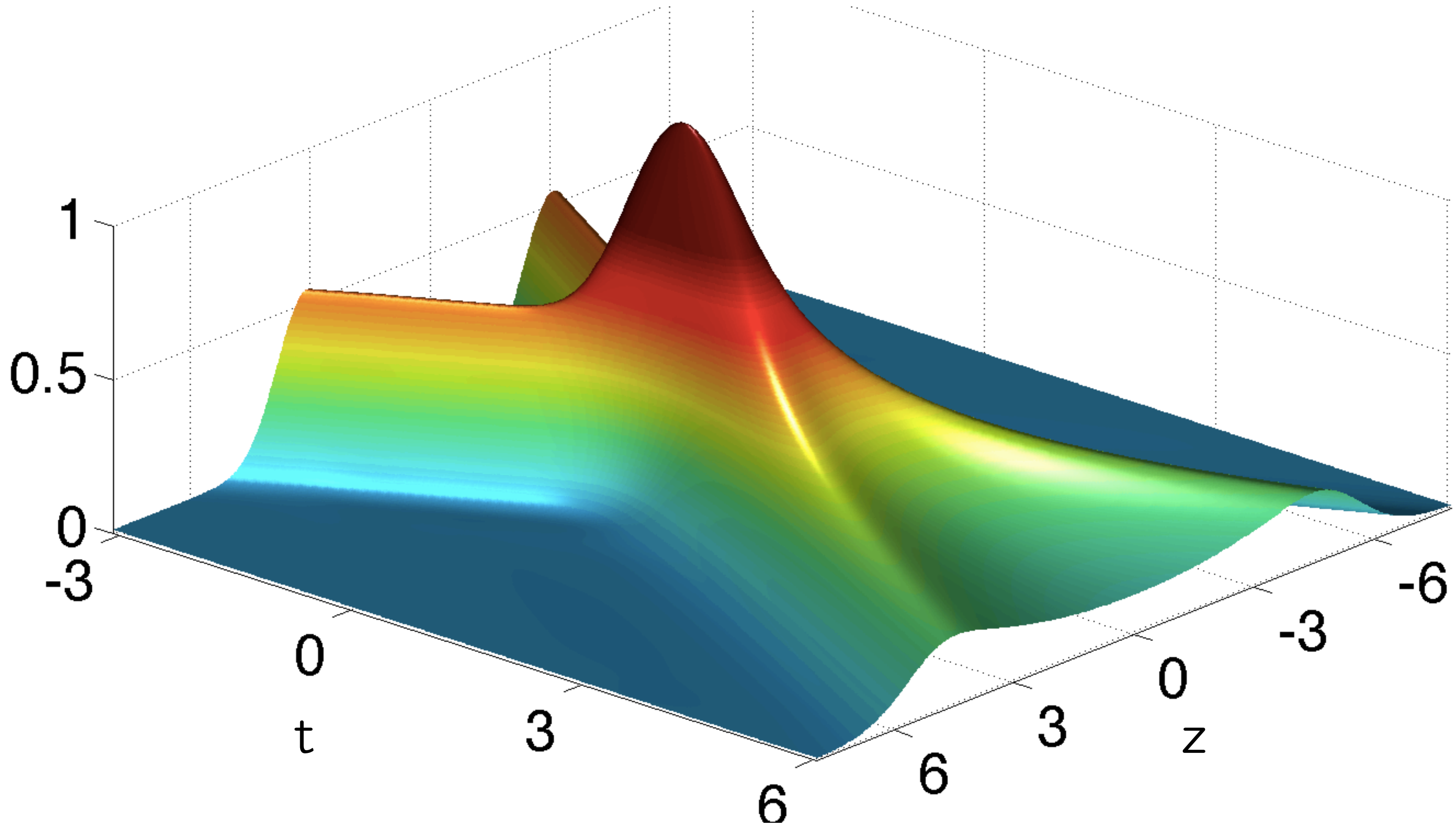
- Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large η/s) or if it takes too long for the droplet to equilibrate.

- 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.

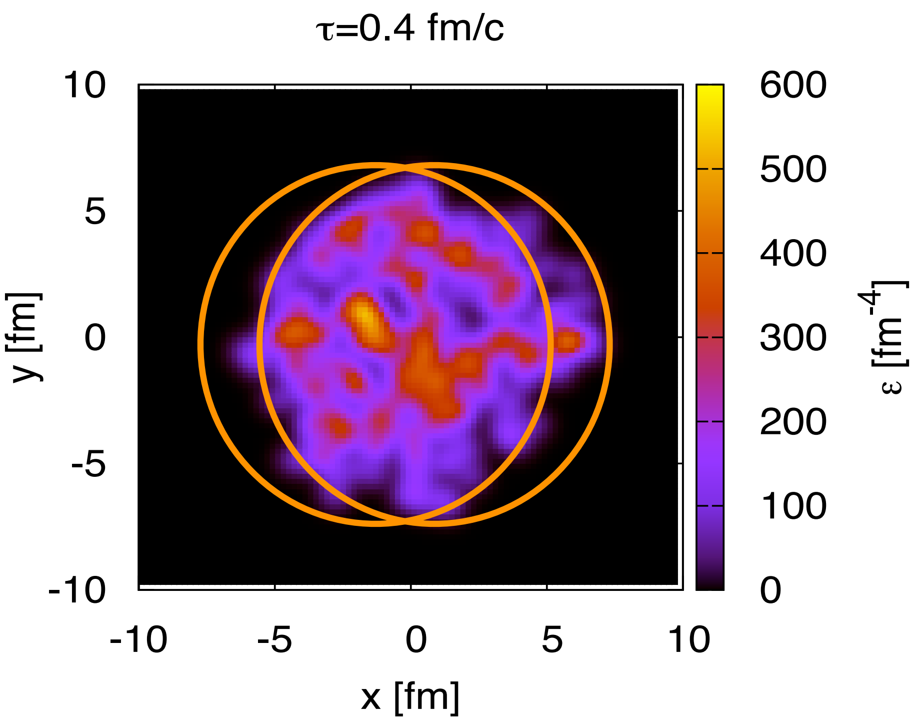
- But, is it really? How rapidly does equilibration occur in a strongly coupled theory?

Colliding Sheets of Energy in a Strongly Coupled Theory



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 arXiv:1011.3562

Determining the Shear Viscosity of QGP with Correlations: Beating Down the Initial State Uncertainties



1. Characterize energy density with ellipse
   - Elliptic Shape gives elliptic flow

$$v_2 = \langle \cos 2\phi_{\mathbf{p}} \rangle$$

2. Around almond shape are *fluctuations*
   - Triangular Shape gives v_3 (Alver, Roland)

$$v_3 = \langle \cos 3(\phi_{\mathbf{p}} - \Psi_3) \rangle$$

3. Hot-spots give *correlated* higher harmonics
   - Systematized and simulated

Different harmonics damped differently by viscosity, and depend differently on system size, momentum. Experimental data on correlations of higher harmonics can vastly overconstrain hydrodynamic predictions for QGP, and hence determination of η/s. Maybe even $\eta/s(T)$.

Many groups working on this; expect progress at this meeting. Slide from Teaney; image from Schenke, Jeon, Gale.

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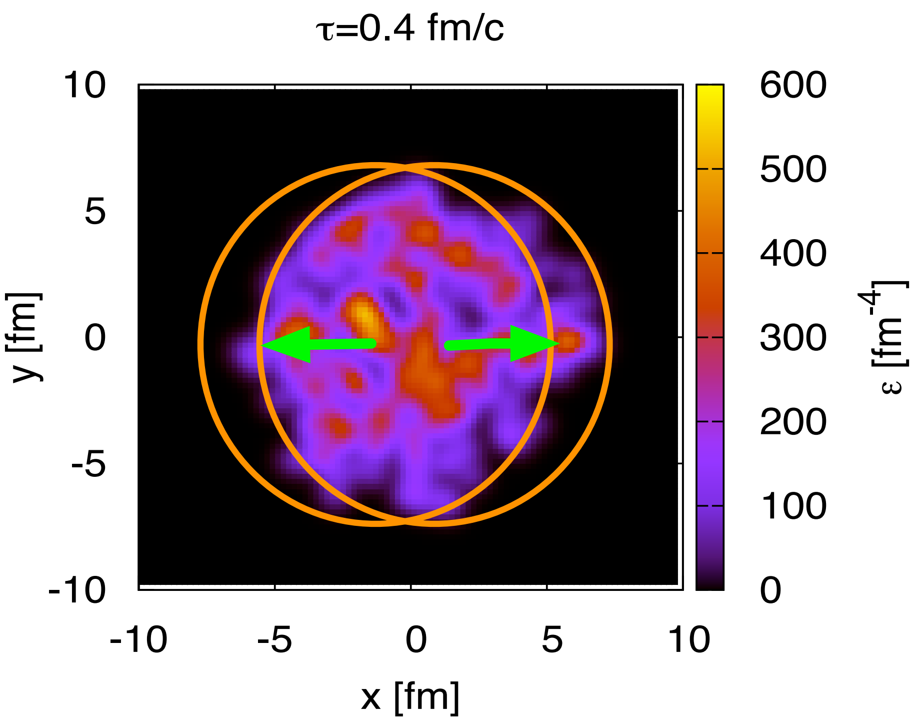

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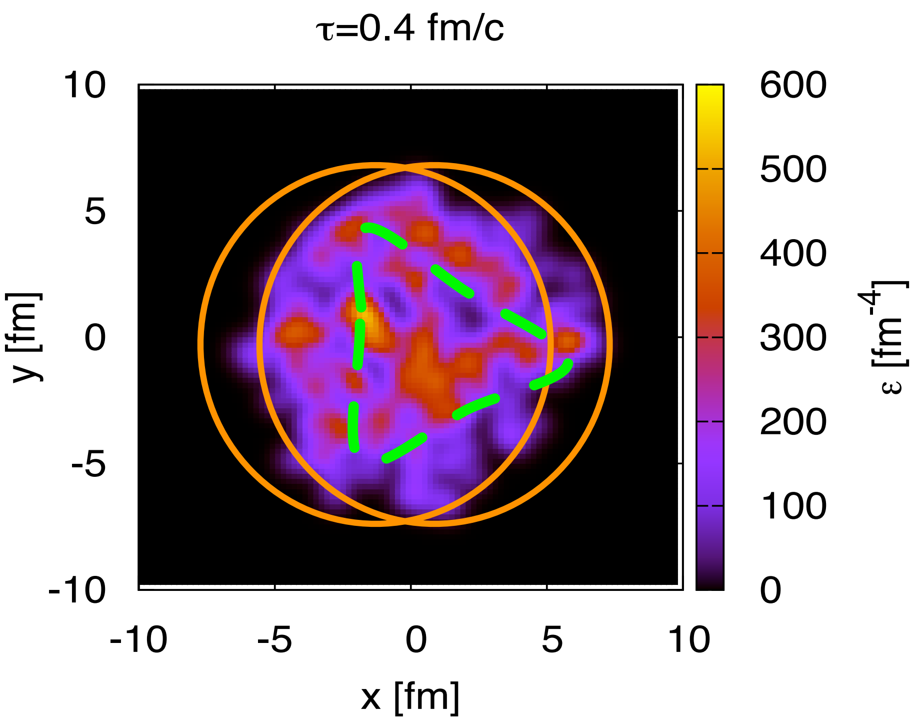

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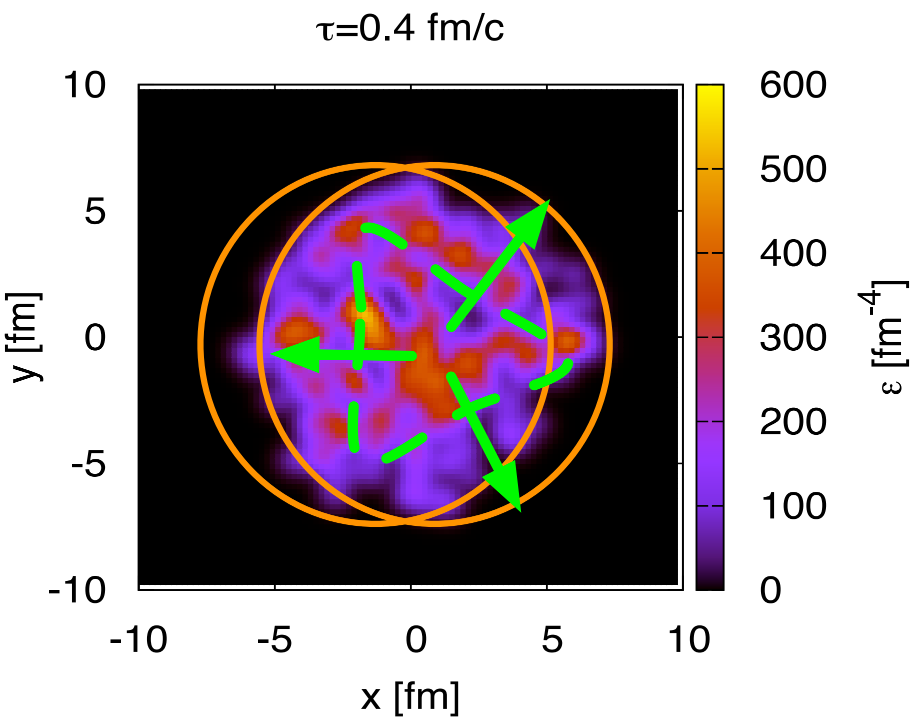

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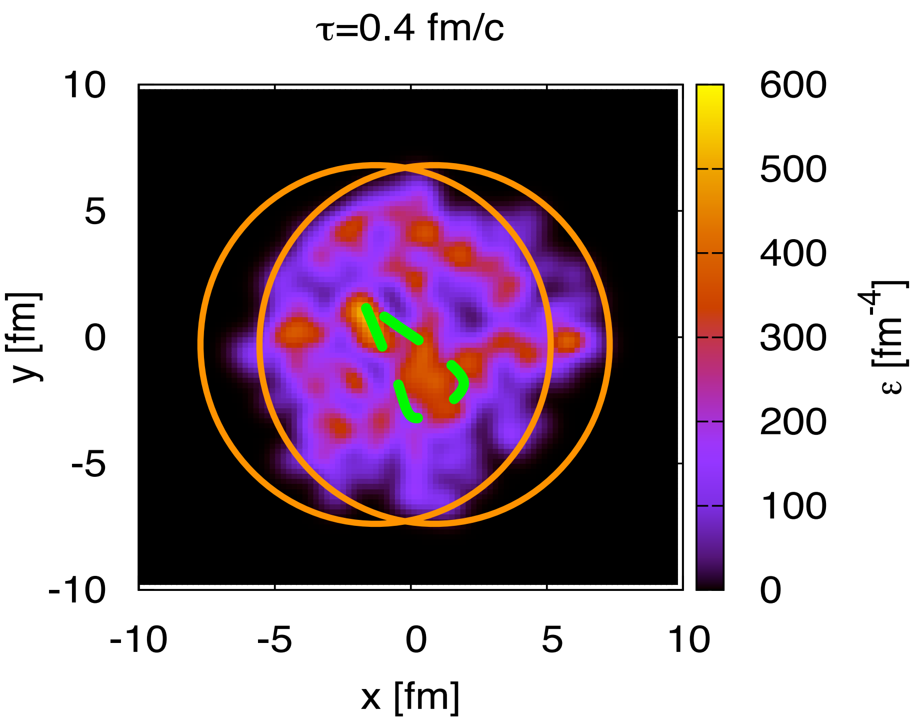

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Ultracold Fermionic Atom Fluid

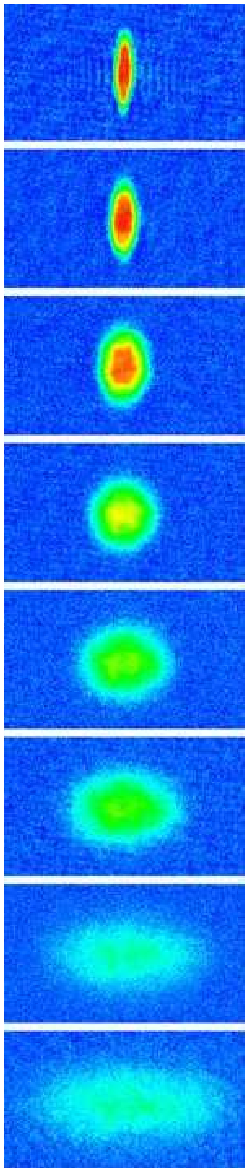
- The one terrestrial fluid with η/s comparably small to that of QGP.

- NanoKelvin temperatures, instead of TeraKelvin.

- Ultracold cloud of trapped fermionic atoms, with their two-body scattering cross-section tuned to be infinite. A strongly coupled liquid indeed. (Even though it's conventionally called the "unitary Fermi gas".)

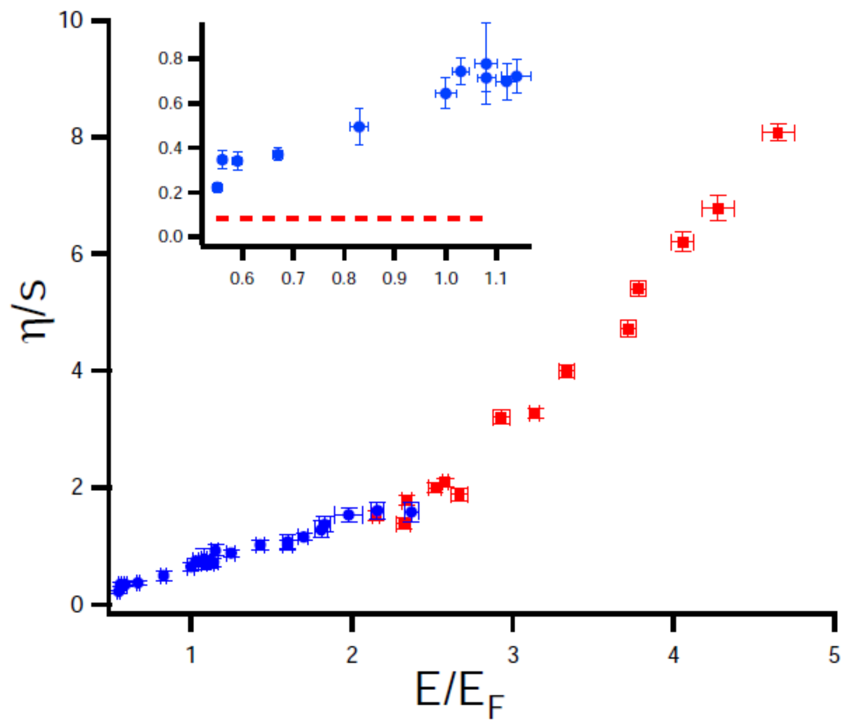
- Data on elliptic flow (and other hydrodynamic flow patterns that can be excited) used to extract η/s as a function of temperature...

Viscosity to entropy density ratio



consider both collective modes (low T)

and elliptic flow (high T)



Cao et al., Science (2010)

$$\eta/s \leq 0.4$$

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 the case of the 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.)
- 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.
- 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.**

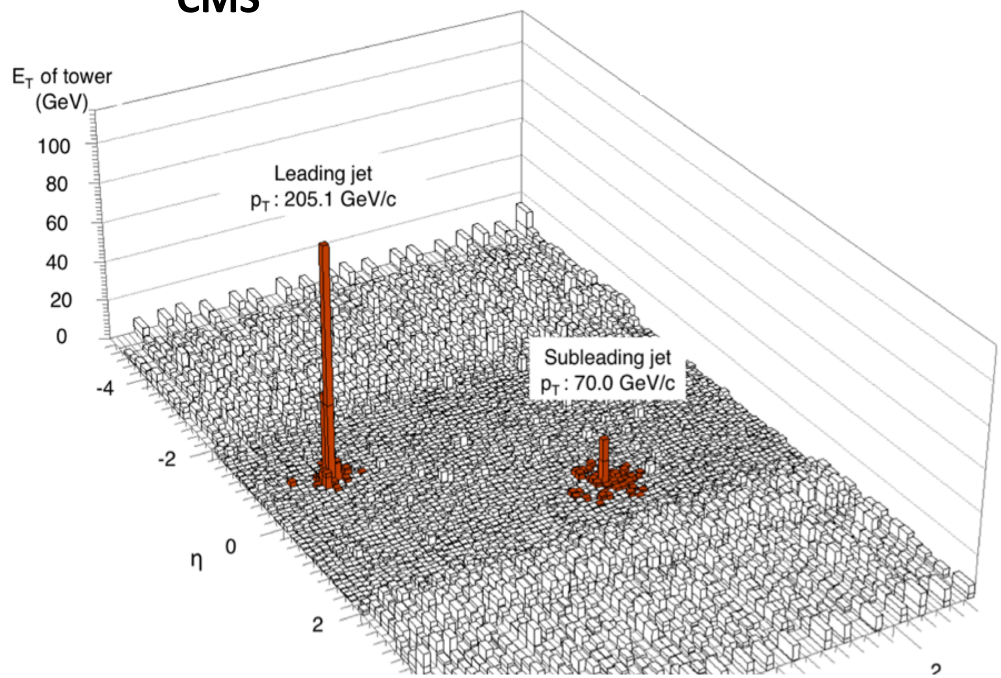
- **We can quantify the properties and dynamics of Liquid QGP at it's natural length scales, where it has no quasiparticles.**

- **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.**

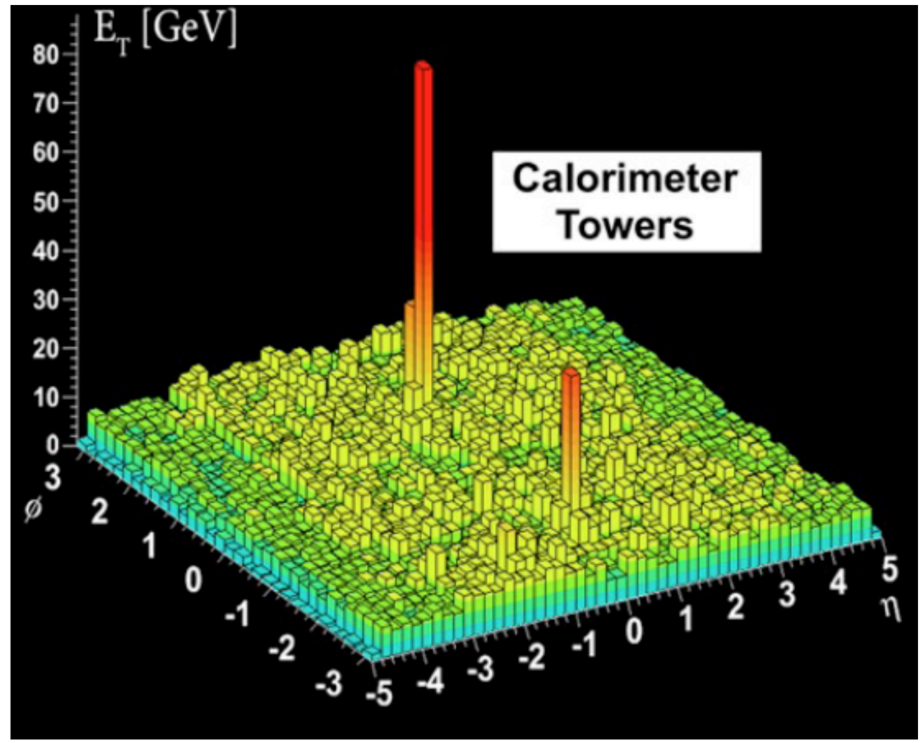
- **The LHC offers new probes and opens new frontiers.**

Jet Quenching at the LHC

CMS



ATLAS



A very large effect at the LHC, immediately apparent in single events. 200 GeV jet back-to-back with a 70 GeV jet. Strongly coupled plasma.

A Big Surprise. . . CMS arXiv:1102.1957

- **The 70 GeV jet looks like a 70 GeV jet in pp collisions. The "missing" 130 GeV of energy is *not* in the form of a spray of softer particles in and around the jet.**

- **Contradicts the many pre-LHC analyses of jet quenching built upon a picture of a hard parton losing energy by radiating nearly collinear gluons. In such a picture, if a 70 GeV jet gets out it must be surrounded by its debris.**

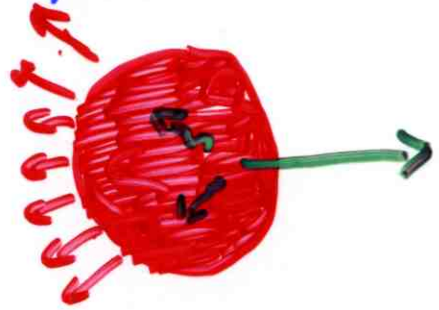
- **Also, 70 GeV jet seems to be back-to-back with the 200 GeV jet; no sign of transverse kick.**

- **The "missing" 130 GeV of energy is in the form of many ~ 1 GeV particles at large angle to the jet directions.**

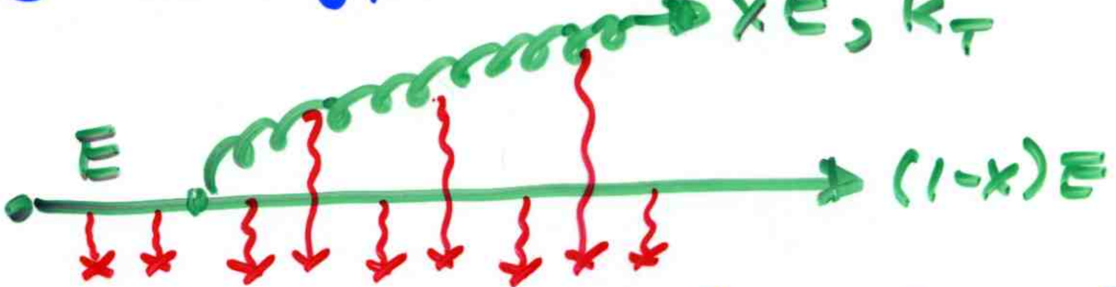
- **Conventional picture of jet quenching, based on weakly coupled intuition, not valid even for 200 GeV jets. Even 200 GeV jets not "seeing" the quasiparticles at short distances.**

JET QUENCHING

Further evidence that QGP@RHIC is strongly coupled.



Radiative energy loss



dominates in high E limit. ($E \gg k_T \gg T$)

<u>If</u> so (RHIC? LHC?), energy loss sensitive to medium through <u>one</u> parameter $\hat{q}$, k_T^2 picked up by radiated gluon per distance L travelled.

Spectrum of radiated gluons: $\omega \frac{dI}{d\omega} \sim \alpha \sqrt{\frac{\hat{q}}{\omega}}\, L$

Energy loss $\Delta E \sim \alpha \hat{q} L^2$

for $\omega < \hat{q} L^2$

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- **Conventional picture of jet quenching, based on weakly coupled intuition, not valid even for 200 GeV jets. Even 200 GeV jets not "seeing" the quasiparticles at short distances.**

- As if the initially-200-GeV parton just heats the plasma it passes through ("makes a little extra plasma") and then emerges and hadronizes like a vanilla 70 GeV parton.

- Or, as if a jet can propagate through the plasma, losing energy and heating up the plasma as it goes, but without spreading in angle.

- We need† a strongly coupled approach to jet quenching, even if just as a foil with which to develop new intuition.

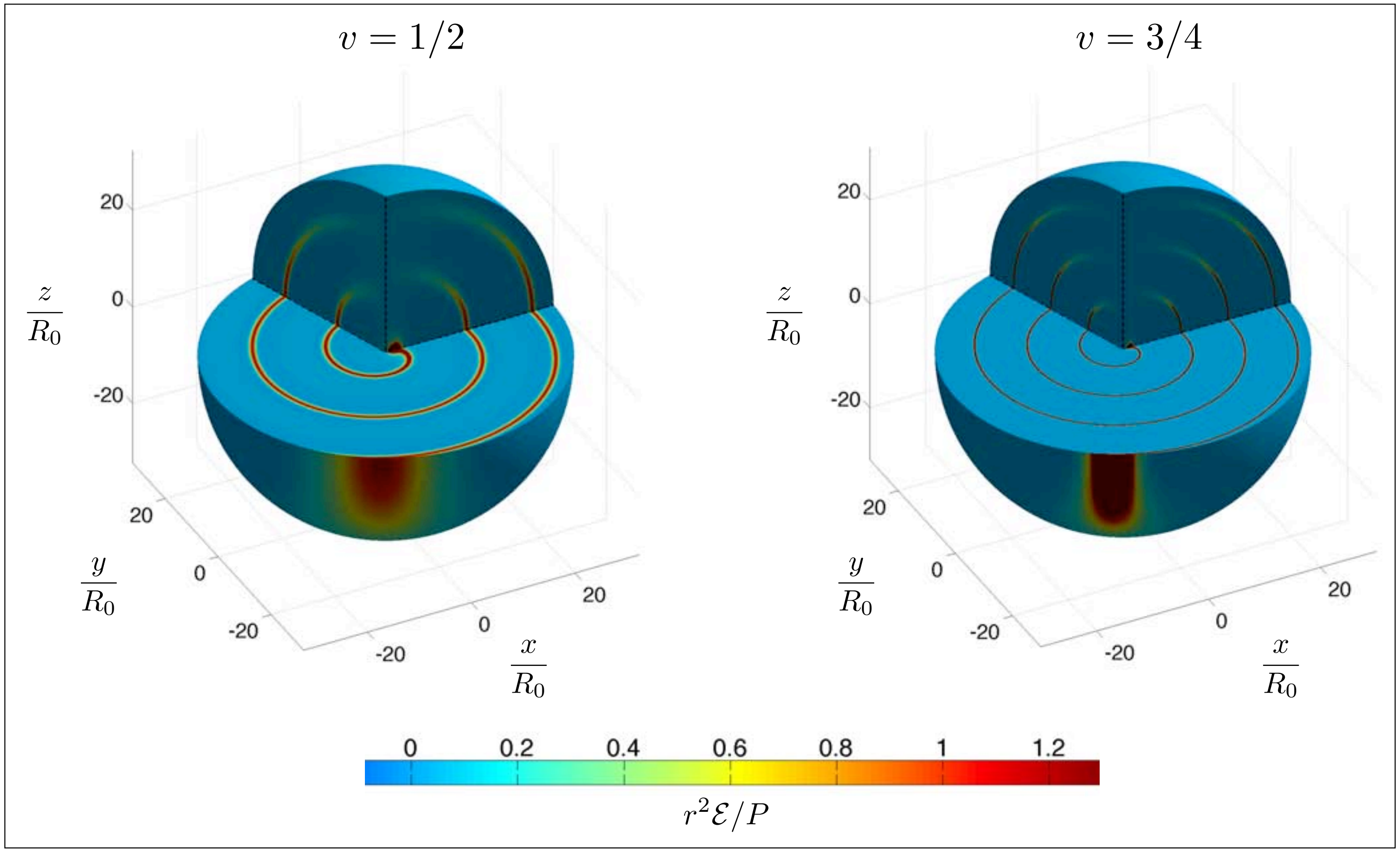
- Problem: jet production is a weakly-coupled phenomenon. There is no way to make jets in the strongly coupled theories with gravity duals.

- But we can make a beam of gluons...

†But, I'm hedging my bets until this big surprise is confirmed in other ways by other detectors. See D'Eramo's talk and Lekaveckas' poster for my work deploying SCET within the conventional picture of jet quenching.

Synchrotron Radiation in Strongly Coupled Gauge Theories

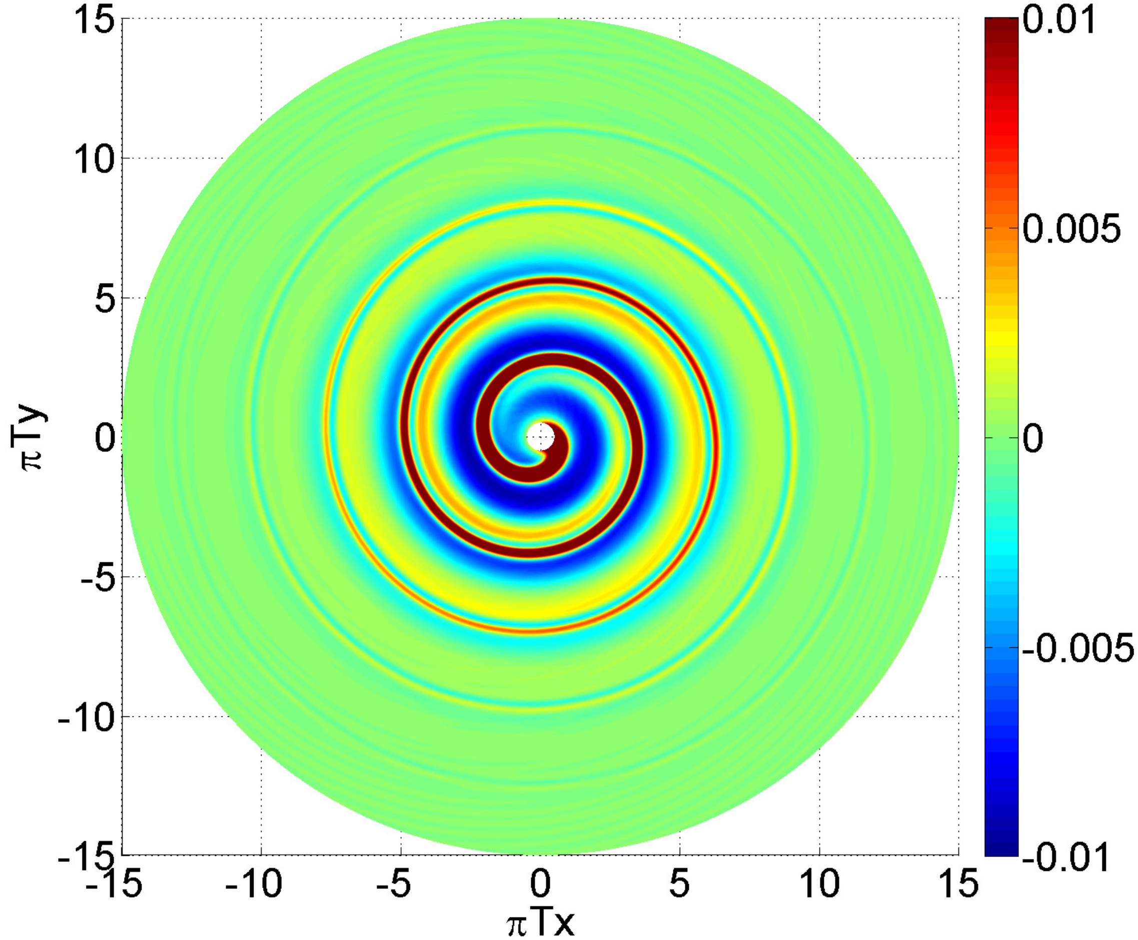
Athanasiou, Chesler, Liu, Nickel, Rajagopal; arXiv:1001.3880



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 Synchrotron Beam

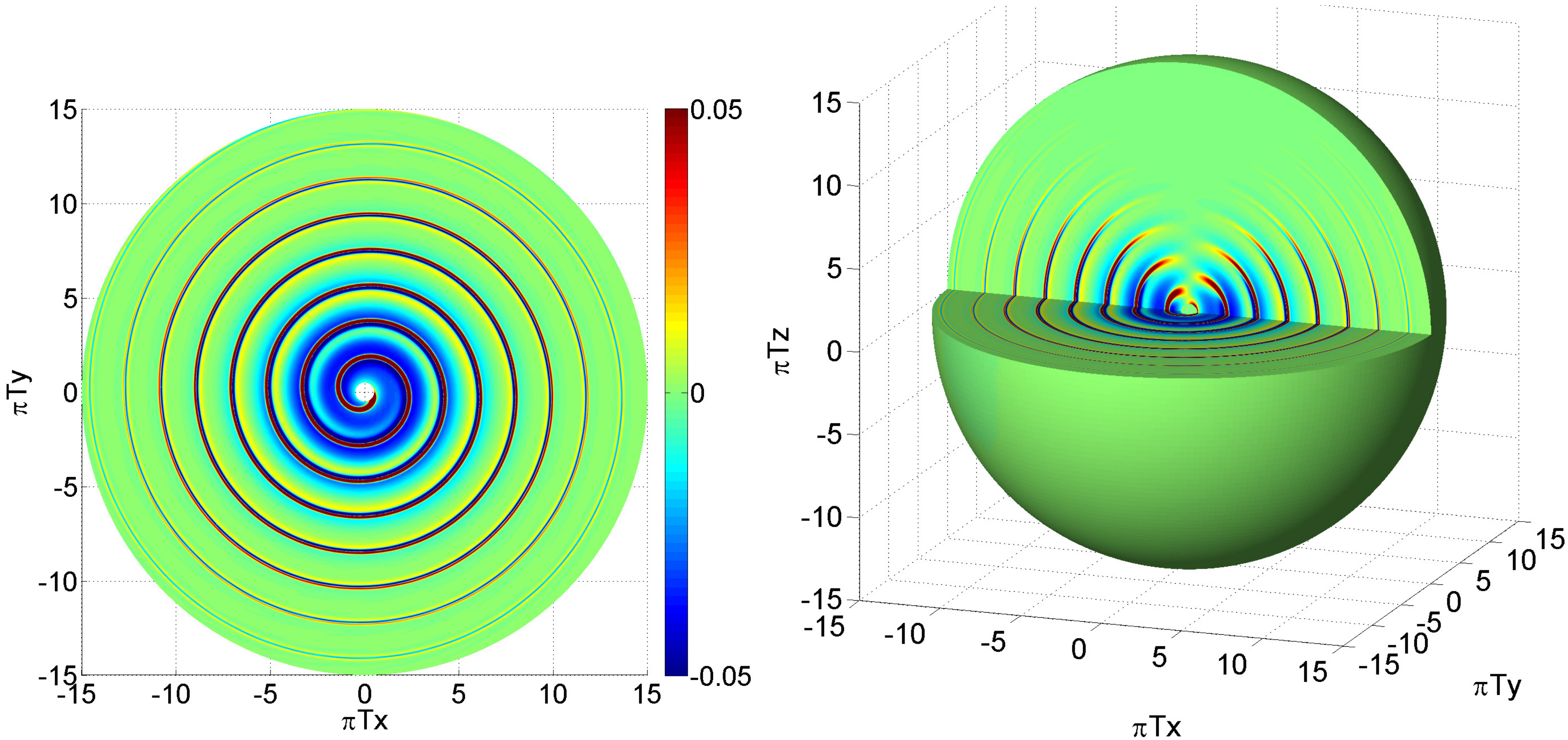
Chesler, Ho, Rajagopal; preliminary



Quark in circular motion ($v = 0.34$; $R\pi T = 0.15$) through the strongly coupled plasma radiates synchrotron radiation that dissipates, ***and heats the plasma behind it*****.**

Quenching a Synchrotron Beam

Chesler, Ho, Rajagopal; preliminary



This time, $v = 0.5 \rightarrow$ higher energy gluon beam. Dissipates *without spreading in angle*. **No sign of spreading of the angular extent of the beam in either azimuthal or polar angle.**

Jet Quenching in Liquid QGP

- **We're back at the blind-folk and the elephant stage. Lets hope for progress at this meeting.**

- **A beam of gluons loses its energy by heating the strongly coupled plasma it propagates through, not by spreading. At least reminiscent of jet quenching at the LHC.**

- **Pre-equilibrium parton energy loss may be important.**

- **If a high energy jet does not "see" the short-distance quasiparticles, perhaps quarkonia or photons will.**

- **Upsilons have the virtue of being small...**

- **At some short length scale, a quasiparticulate picture of the QGP 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.**

Heavy quarks?

- **In strongly coupled plasmas with gravitational descriptions, heavy quarks lose energy according to $\frac{dp}{dt} = -F(v)$. The force F depends on v but is independent of the heavy quark mass M.** Herzog et al; Gubser; Casalderrey-Solana, Teaney
- **Similar behavior in these theories and in the strongly coupled plasma of QCD.** Chesler, Yaffe; Neufeld, Muller, Ruppert
- **Distinctive predictions for experiment, once b and c quarks can be separated, from the prediction of same energy loss for b and c quarks** *with the same v.* Horowitz, Gyulassy
- **If these predictions are confirmed by experiment, it means that the heavy quarks are not behaving like objects of size $1/M$; they are dressing themselves up (with fields) until they have a larger, M-independent, size. Heavy quarks can't "see" short-distance quasiparticles.**
- **Upsilons have the virtue of being small, and color-singlet.**

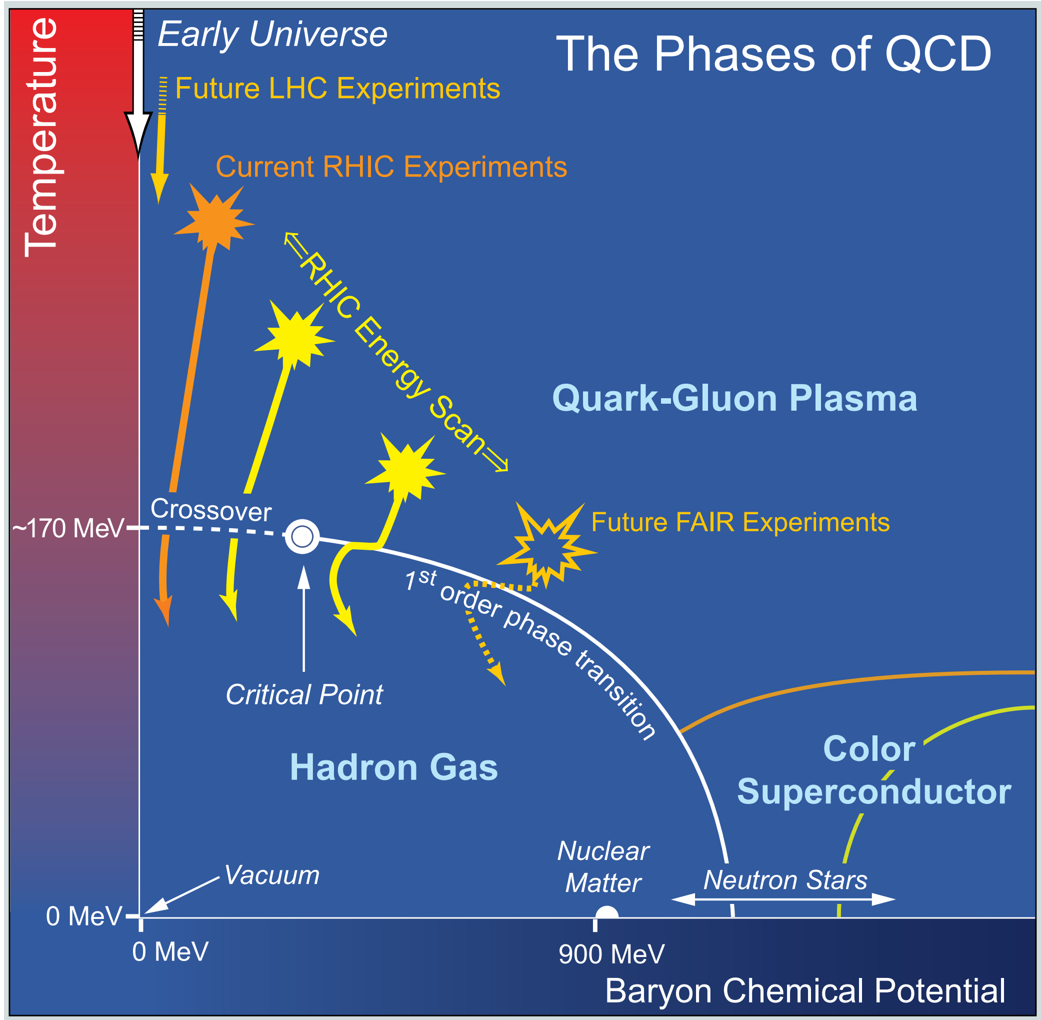
A Grand Challenge

- 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 quasiparticulate picture of the QGP 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.

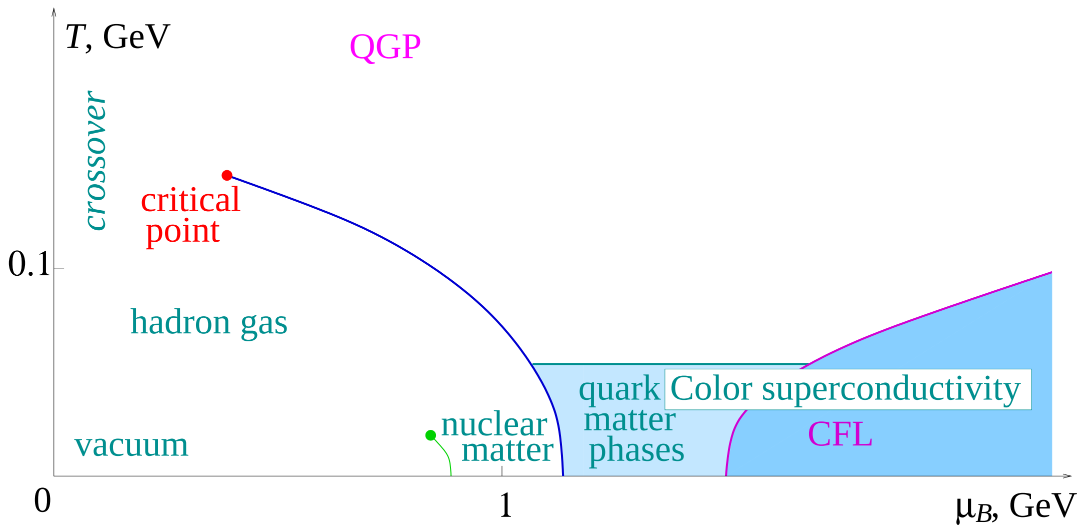
Seeking the QCD Critical Point

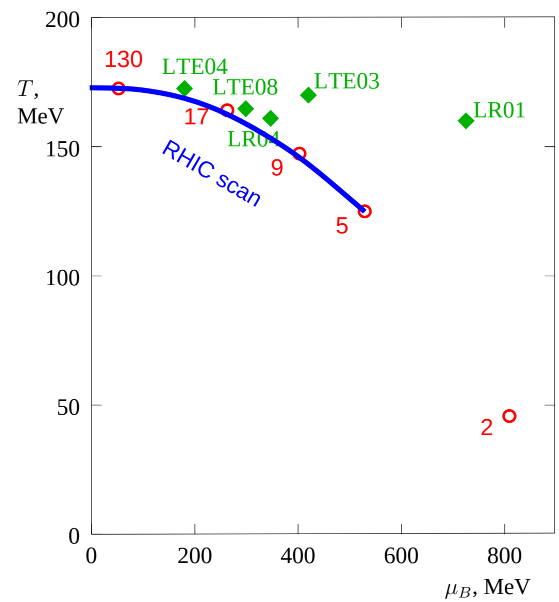


2007 NSAC Long Range Plan

Another grand challenge... Data from first phase of RHIC Energy Scan expected at QM11. First, a theory development...

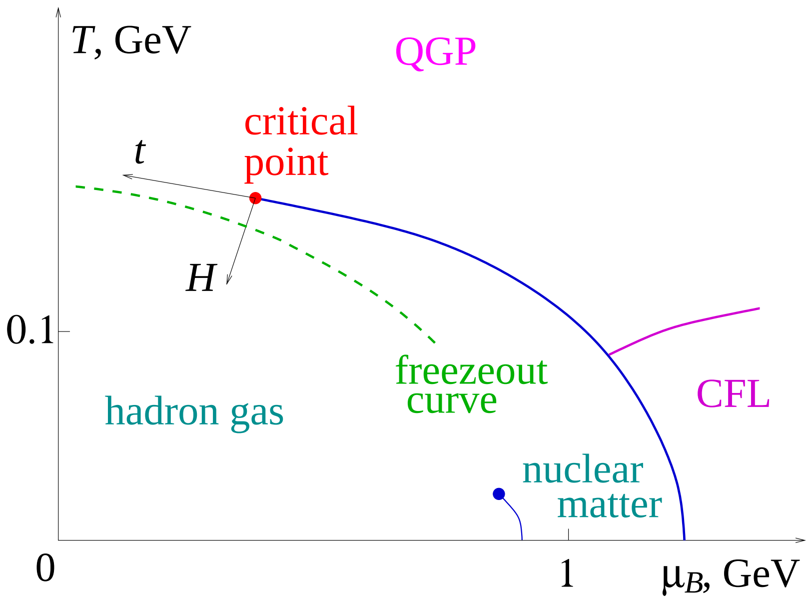
QCD phase diagram, critical point and RHIC

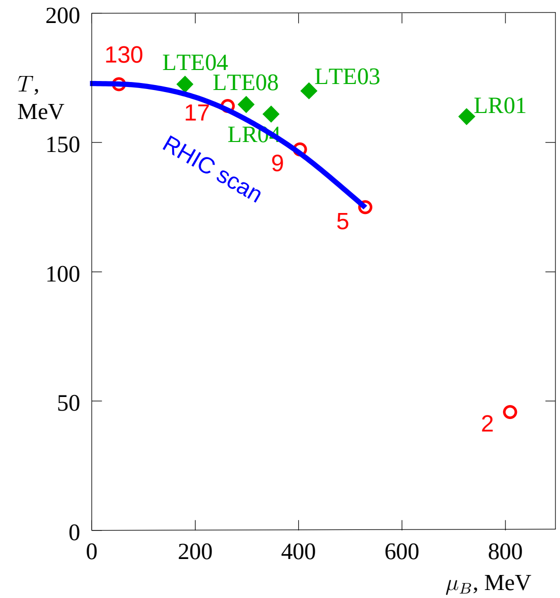




- Models (and lattice) suggest the transition becomes 1st order at some μ_B.
- Can we observe the critical point in heavy ion collisions, and how?
- Near critical point fluctuations grow and become more non-Gaussian.
- Challenge: develop measures most sensitive to the critical point and use them to locate the critical point by scanning in $\sqrt{s}$ and therefore in $\mu_{\text{freezeout}}$.
- Example: kurtosis (of the event-by-event distribution of the number of protons, pions or protons-antiprotons) depend strongly on the correlation length (ξ^7), which is non-trivial, non-monotonic function of μ and therefore $\sqrt{s}$. And, the prefactor in front of ξ^7 changes sign! Stephanov, 1104.1627

QCD phase diagram, critical point and RHIC





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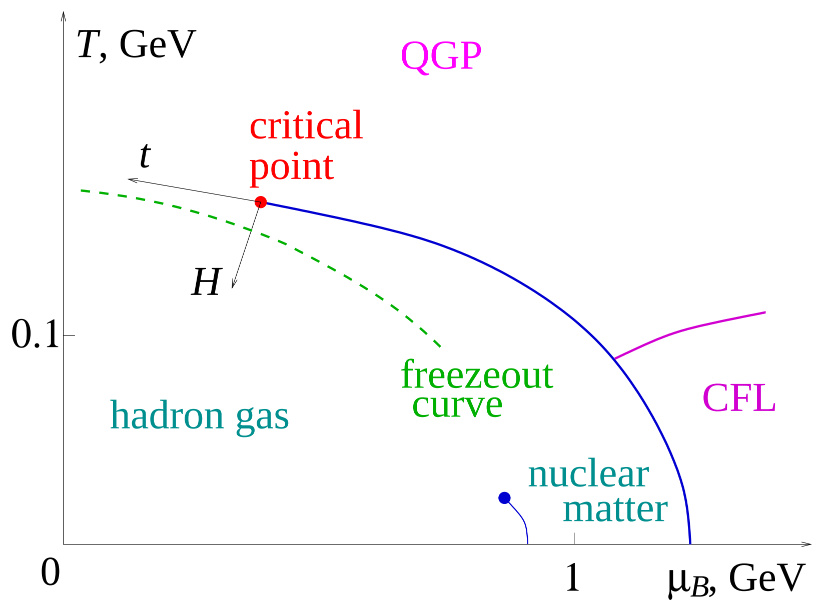

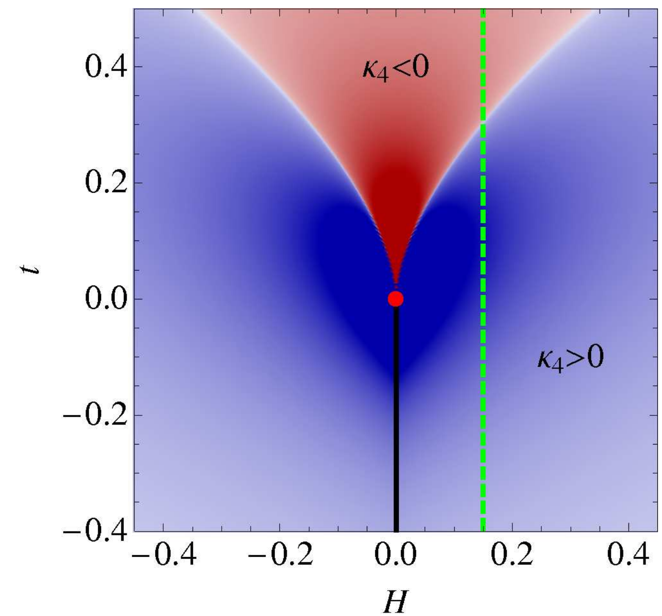

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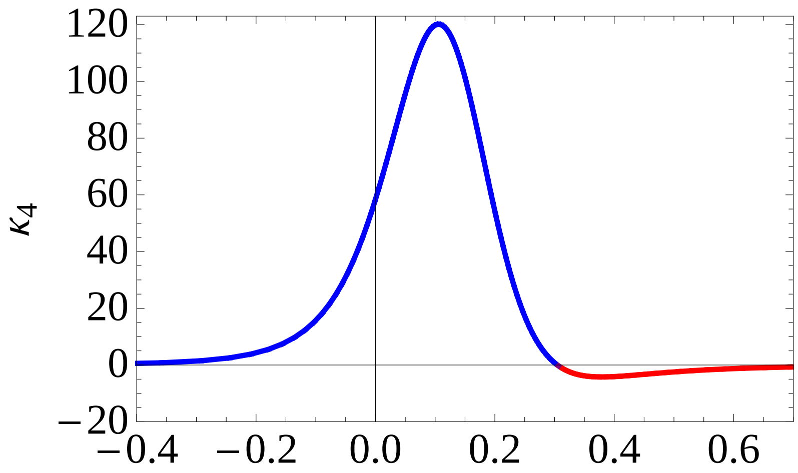
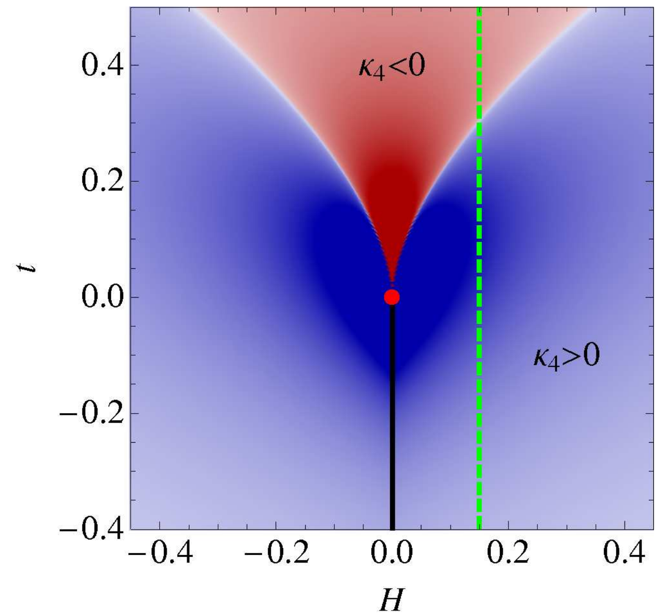
QCD phase diagram, critical point and RHIC

crit. contribution to Kurtosis (arb. units)

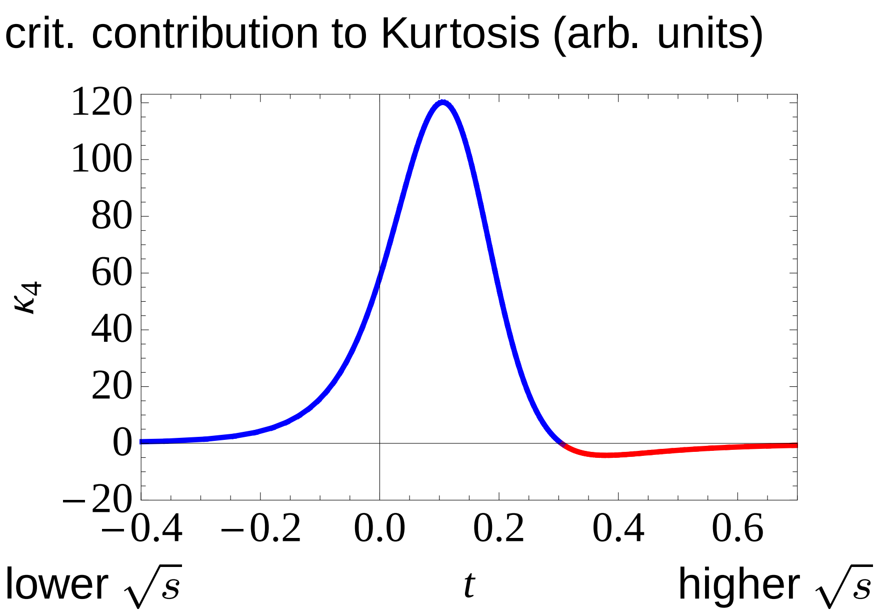


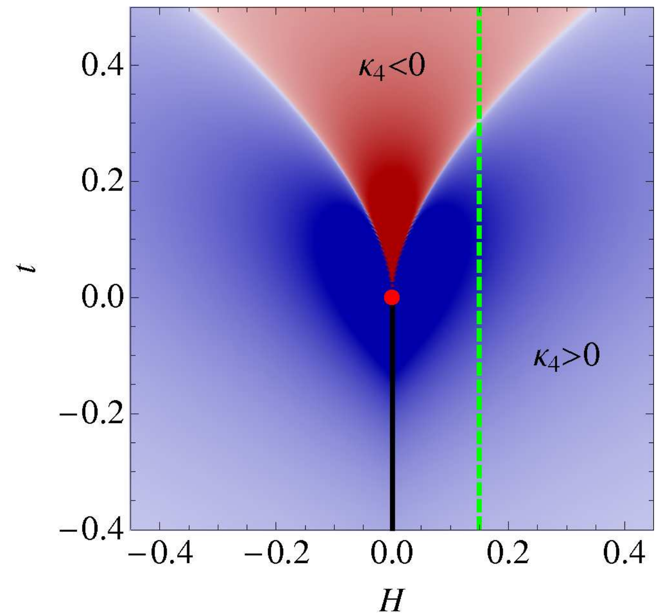
lower $\sqrt{s}$ t higher $\sqrt{s}$



- Models (and lattice) suggest the transition becomes 1st order at some μ_B.
- Can we observe the critical point in heavy ion collisions, and how?
- Near critical point fluctuations grow and become more non-Gaussian.
- Challenge: develop measures most sensitive to the critical point and use them to locate the critical point by scanning in $\sqrt{s}$ and therefore in $\mu_{\rm freezeout}$.
- Example: kurtosis (of the event-by-event distribution of the number of protons, pions or protons-antiprotons) depend strongly on the correlation length (ξ^7), which is non-trivial, non-monotonic function of μ and therefore $\sqrt{s}$. And, the prefactor in front of ξ^7 changes sign! Stephanov, 1104.1627

QCD phase diagram, critical point and RHIC





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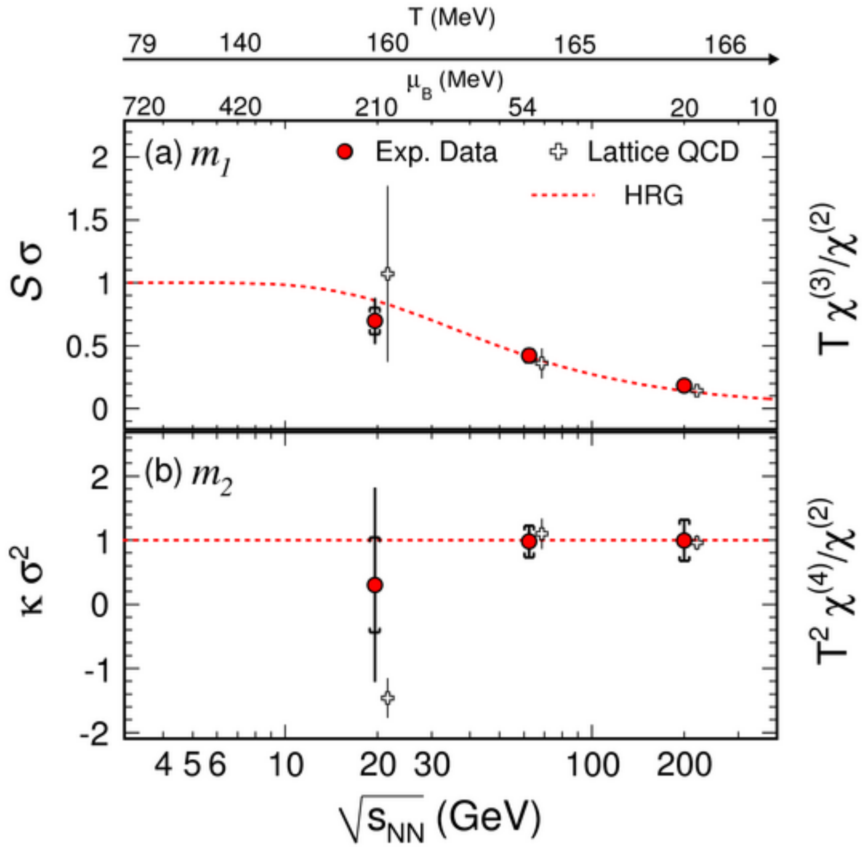
- Once we find the μ (i.e. the $\sqrt{s}$) where the critical contribution to κ_4 is large enough — e.g. the “blue peak” — then there are then robust, parameter-independent, predictions for various ratios of the kurtosis and skewness of protons and pions. Athanasiou, Stephanov, Rajagopal 1006.4636.

pre-QM RHIC and Lattice Data



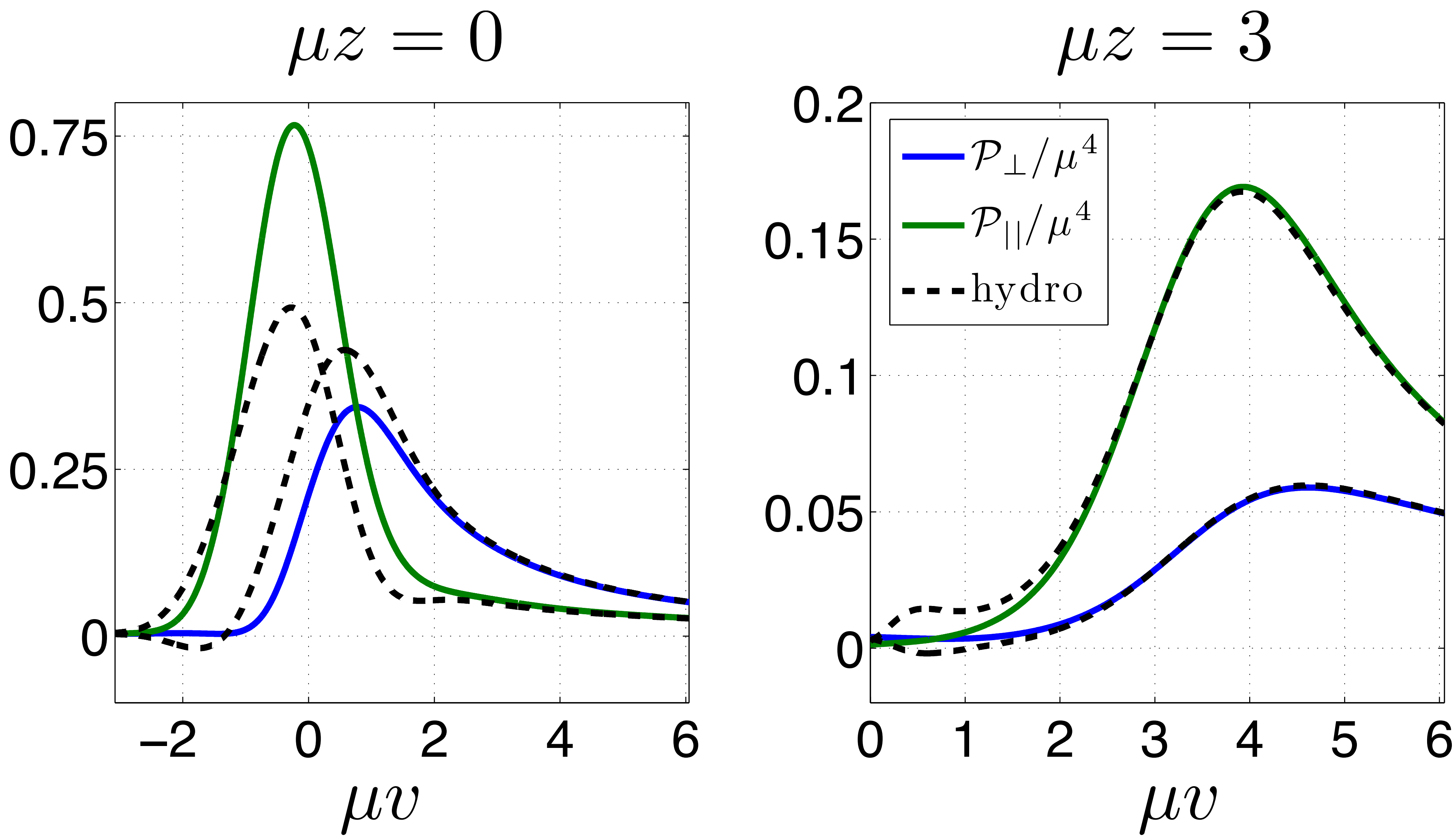
Gupta, Luo, Mohanty, Ritter, Xu, 2011, accepted for publication in Science; data from STAR 2010; lattice calculations from Gavai, Gupta 2011

If $\kappa\sigma^2$ stays below 1 at $\sqrt{s} = 19.6$ GeV, the place to look is just left of there. Data at several new energies this meeting. Further data at $\sqrt{s} = 19.6$ GeV taken a month ago.

Stay Tuned. . .

Lets see how much this One Theorist's View of the Opportunities and Challenges presented to us by the discovery of Liquid Quark-Gluon Plasma has changed by the end of the week that is to come — which will be jam-packed with new data and new ideas, as we step into the LHC+RHIC era.

Comparing to 1$^{\text{st}}$ order hydrodynamics



- Hydro works within 15% for $v > 2.4/\mu$.
  - Estimate for RHIC: $\tau_{\text{hydro}} \sim 0.35$ fm/c.
- $\mathcal{P}_\perp \gtrsim 2\mathcal{P}_{||}$ at $z = 0 \Rightarrow$ viscous effects are important.