Title: Quark Gluon Plasma in QCD, at RHIC, and in String Theory

Date: Jun 04, 2008 09:35 AM

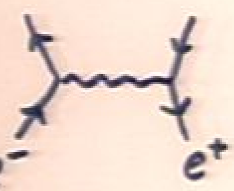
URL: http://pirsa.org/08060041

Abstract:

WHAT IS QCD?

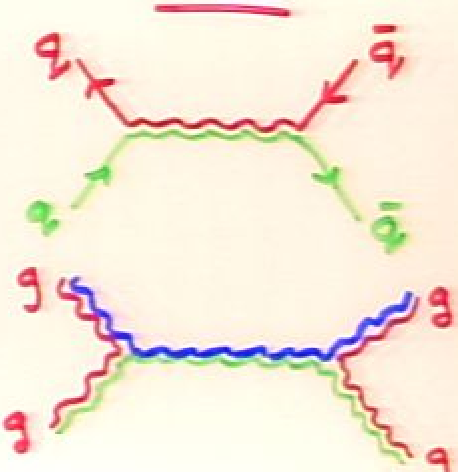
- A theory of quarks and gluons
- Its Lagrangian suggests it is not too different from QED, which is a theory of electrons and photons:

QED



e^-: charge -1
γ: neutral

QCD



q: charge r, g or b
gluons: also charged

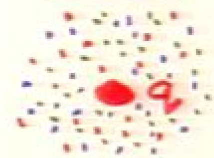
ASYMPTOTIC FREEDOM

Gross, Wilczek, Politzer (1973)

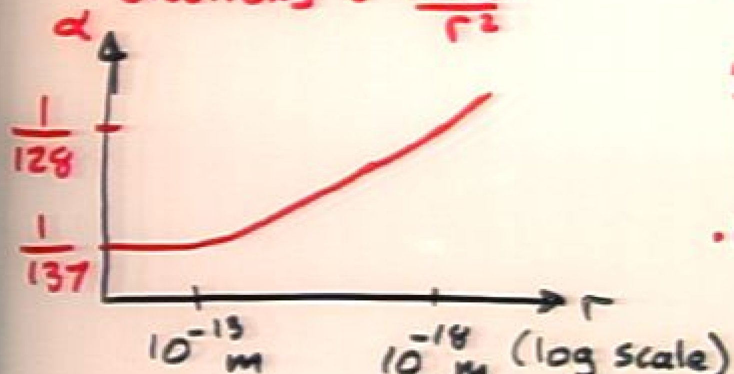
In quantum f[illegible] theory, the vacuum is a medium which can screen charge.

QED

QCD

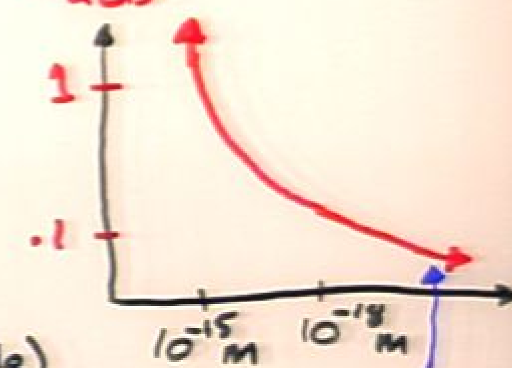


α: Force between electrons $\sim \frac{\alpha(r)}{r^2}$



↑ experiments at CERN

Coupling "constants" not constant. Depend on scale at which you probe.



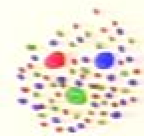
asymptotic freedom, or anti-screening.

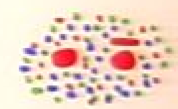
(That's why Friedman, Kendall, Taylor were able to see ^ quarks.)
weakly interacting

WHAT DOES QCD DESCRIBE?

It is an experimental fact that in the world around us quarks and gluons occur only in colorless, heavy packages:

protons, neutrons,...
pions, kaons,....



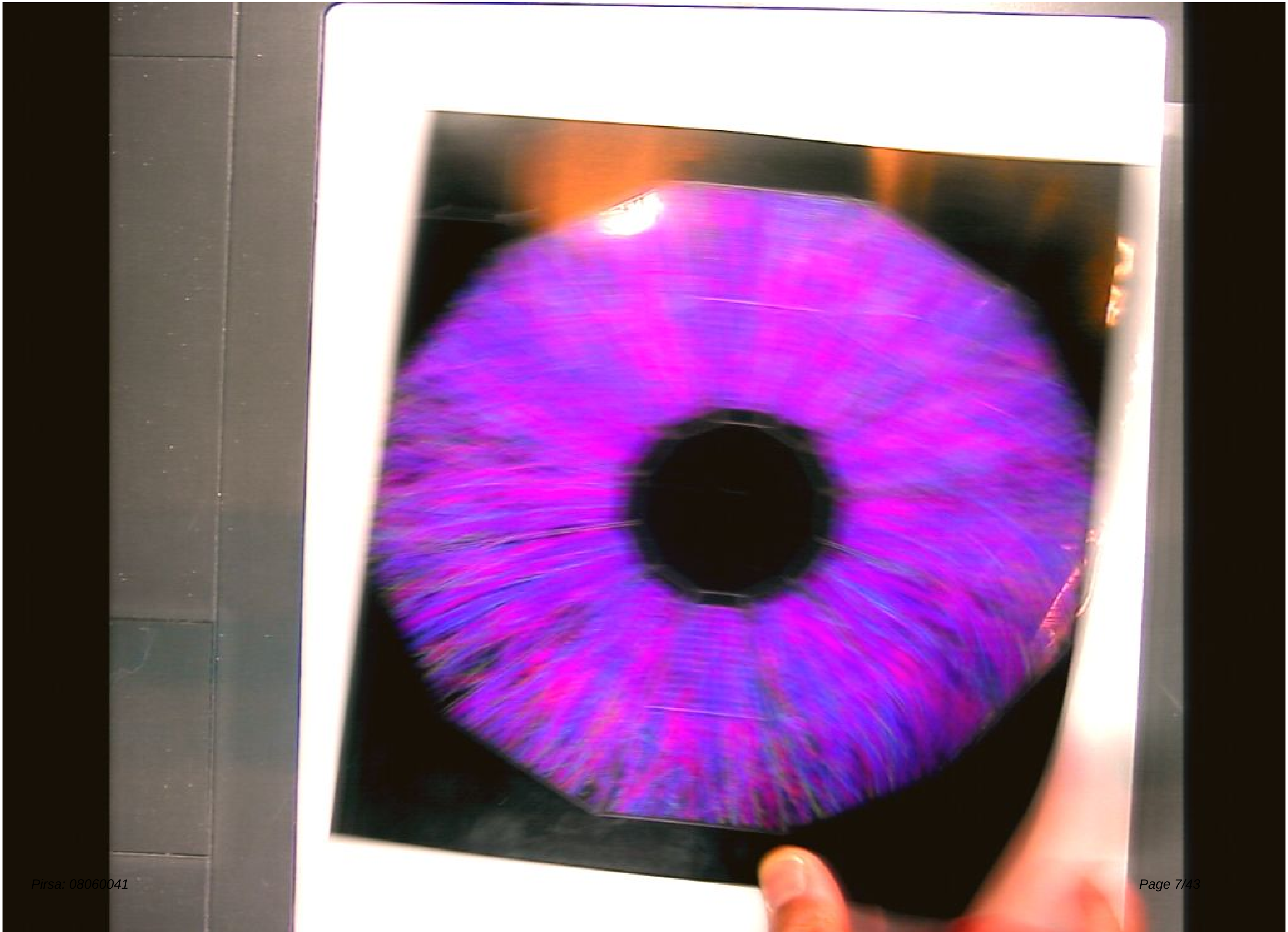


These hadrons are the quasiparticles of the QCD vacuum.

They, in turn, make up everything from nuclei to neutron stars, and thus most of the mass of you and me.

QUARK-GLUON PLASMA

- The $T \to \infty$ phase of QCD
- Entropy wins over order $\Rightarrow$ symmetries of this phase must be those of the QCD Lagrangian
- Asymptotic freedom tells us that, for $T \to \infty$, we must have weakly coupled quark and gluon quasiparticles
- Lattice calculations of QCD thermodynamics show a smooth crossover, like ionization of a gas, at $T_c \simeq 175 \pm 15$ MeV, at which hadrons "ionize" and the order that characterizes the QCD vacuum melts....



QUARK-GLUON LIQUID?

Expts @ RHIC suggest that quark-gluon plasma is so strongly coupled at $T \sim 1.5\,T_c$ accessible at RHIC that it is better thought of as a liquid than a gas.

well-described with ideal hydrodynamics (zero m.f.p.)

→ $\dfrac{\text{shear viscosity}}{\text{entropy density}} = \dfrac{\eta}{s} < \mathcal{O}(0.1)$

[> 0.2 ruled out!

cf: $\eta/s \sim 1$ according to perturbative QCD calculations

$\eta/s \sim 10$ in water

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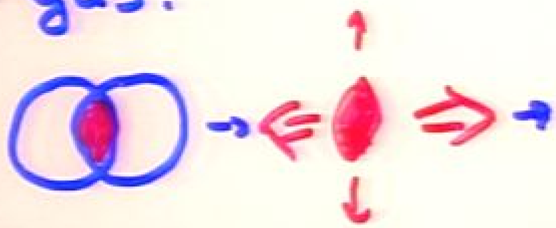

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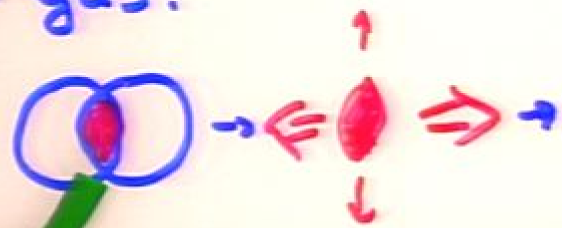

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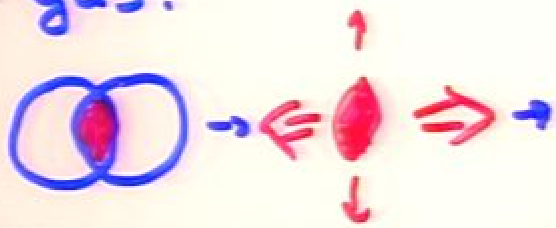

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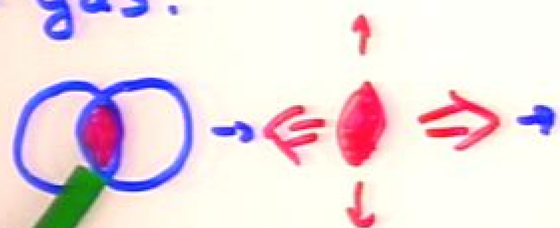

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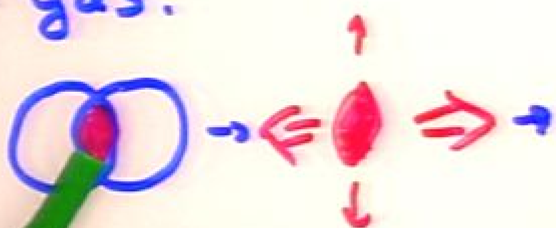

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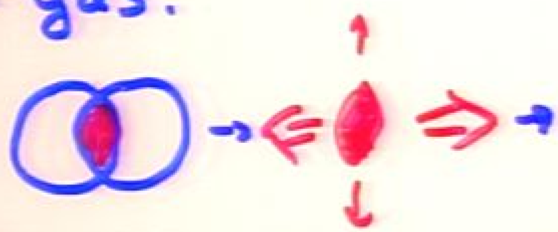

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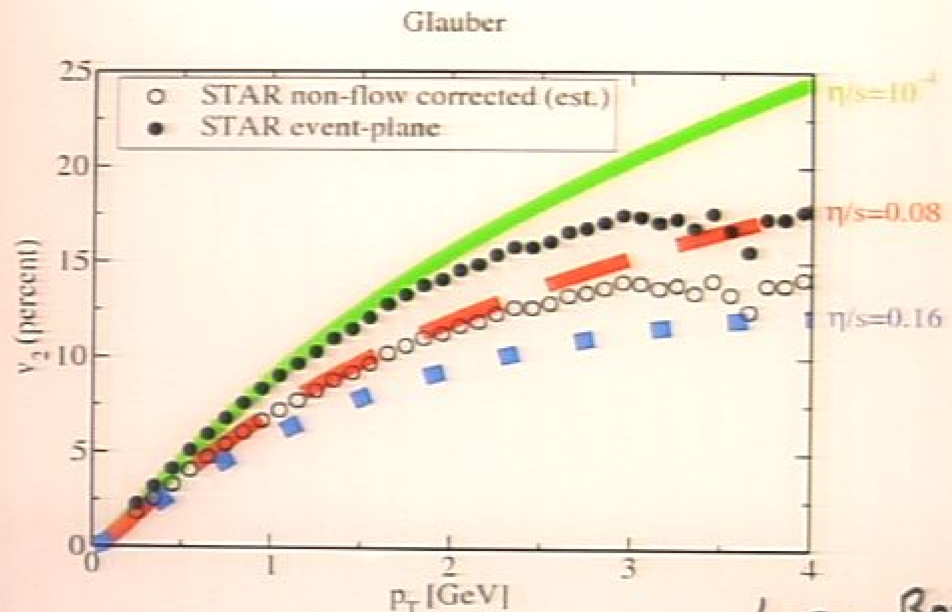
VISCOUS HYDRODYNAMICS



Luzum Romatschke

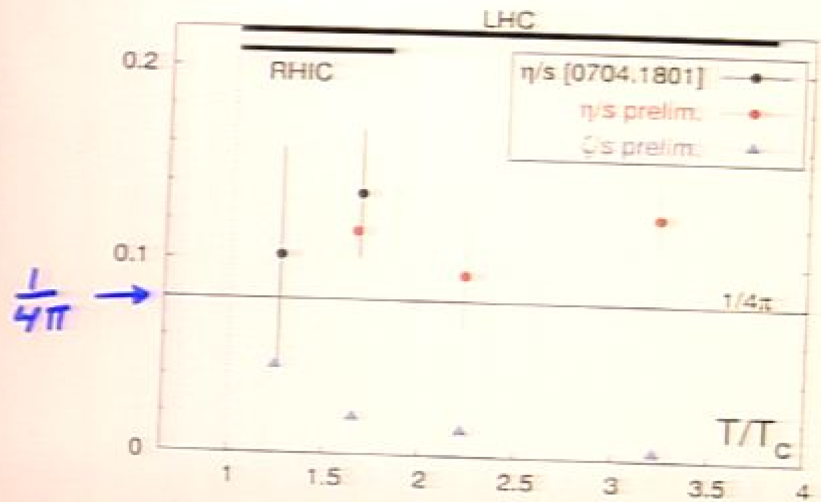
Data: removing non-flow lowers v_2

Hydro: viscosity lowers v_2

Initial Conditions? →

LATTICE CALCULATION OF

η/s & ζ/s IN $N_f = 0$ QCD

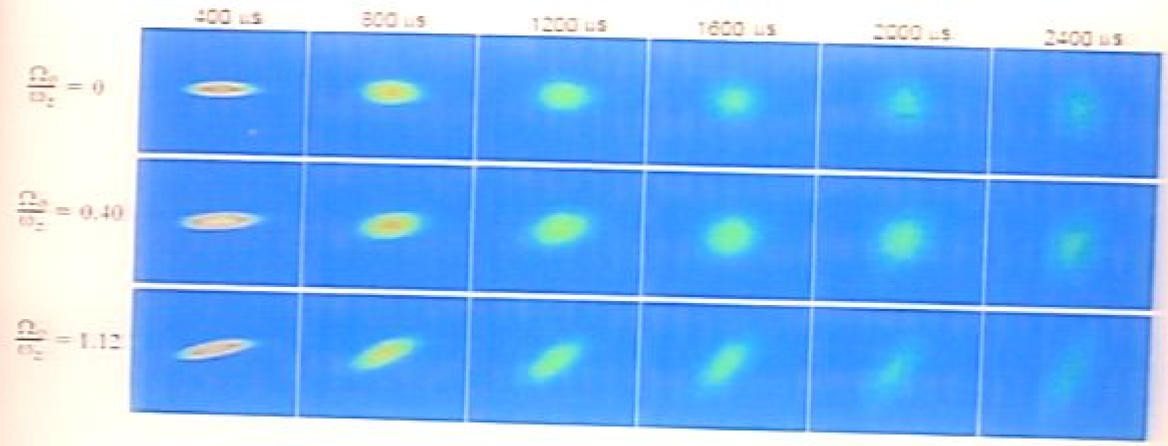


$N_\tau = 8 \quad N_f = 0$ Harvey Meyer '07

- Conformality $\Rightarrow$ $\zeta/s = 0$
  η/s = T-independent
- And, no sign of T-dependence for η/s over $T_{RHIC} \to T_{LHC}$.
- Suggests QGP as liquid-like at LHC as at RHIC.

Expansion of a rotating strongly inter ting Fermi gas

Duke Physics
Atom Cooling and Trapping



Viscosity/entropy density (units of $\hbar / k_B$)

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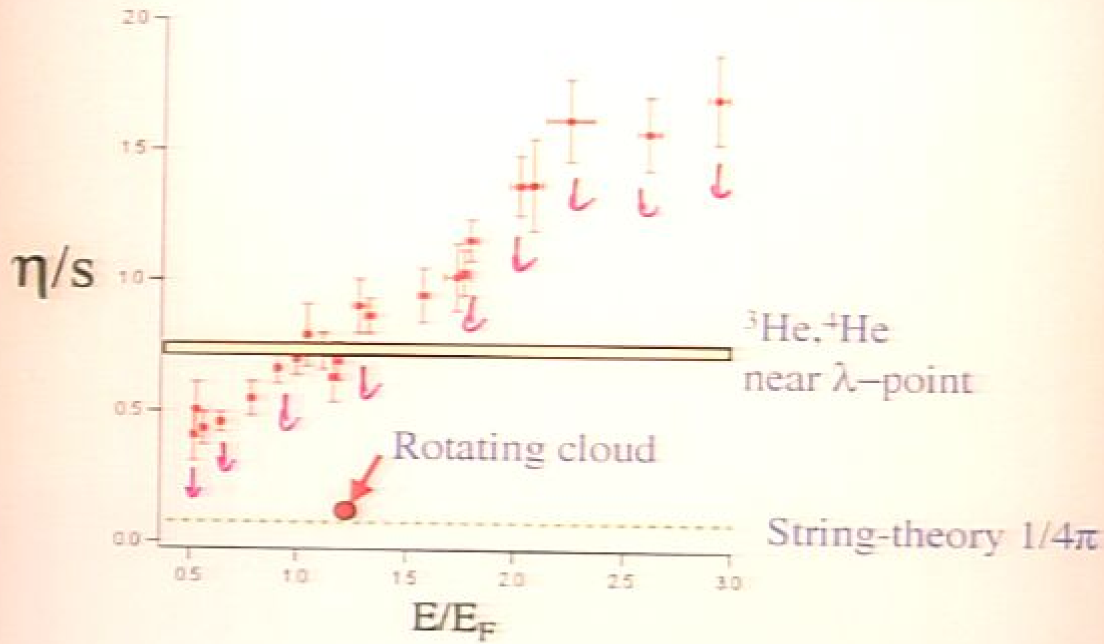

John Thomas, talk at BEC 07, Sant Feliu

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?

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$\mathcal{N}=4$ 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.

PURPOSE OF REST OF THIS TALK

- Describe some of the insights into properties of strongly coupled plasmas via calculations done in $\mathcal{N}=4$ SYM and the infinite classes of other gauge theories dual to gravity in higher dimensional spacetime.
- Because of time constraints, I will not describe how the calculations that have led to these insights are done. I am happy to do so privately. All of them can be done by undergraduates, once you learn the rules.

THERMODYNAMICS

In the $N_c\ \infty$, $\lambda \to \infty$ limit,

$$\frac{\mathcal{E}_{\lambda=\infty}}{\mathcal{E}_{\lambda=0}} = \frac{P_{\lambda=\infty}}{P_{\lambda=0}} = \frac{S_{\lambda=\infty}}{S_{\lambda=0}} = \frac{3}{4}$$

Gubser Klebanov Peet Tseytlin...

- Teaches us that thermodynamics of very weakly coupled plasmas and very strongly coupled plasmas can be rather similar.
- Reminds us that (approximate) conformality above T_c need not mean weak coupling. → FIG.
- $\frac{1}{\lambda^{3/2}}$ corrections known. [$\frac{3}{4}$ becomes 0.77 for $\frac{g^2}{4\pi} = \frac{1}{2}$, $N_c = 3$ → $\lambda = 6\pi$]
- $\frac{1}{N_c^2}$ corrections not known

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SHEAR VISCOSITY

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

Policastro, Starinets, Son

- For *any* theory with a gravity dual, in the $N_c^2 \to \infty$, $\lambda \to \infty$ limit.
- Examples known for theories that are:
  - conformal or not
  - confining at $T=0$ or not
  - have fundamentals or not
  - supersymmetric or not
  - varying numbers of degrees of freedom
- $\frac{1}{\lambda^{3/2}}$ corrections known.

  [$\frac{1}{4\pi}$ becomes $\frac{1.25}{4\pi}$ for $\lambda = 6\pi$]
- $\frac{1}{N_c^2}$ corrections not known
- $\eta/s \geq \frac{1}{4\pi}$ conjectured as a lower bound for all materials.

Kovtun Son Starinets

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.]

UNIVERSALITY?

Is there a new notion of universality for (nearly) scale invariant liquids?

To what systems does it apply?

- quark-gluon plasma dual to string theory + black hole?
- QCD quark-gluon plasma?
- unitary fermionic atom gas?

  [Aside: whose gravity dual may recently have been found.
  Son; Balasubramanian Mcgreevy; Adams, B, M]

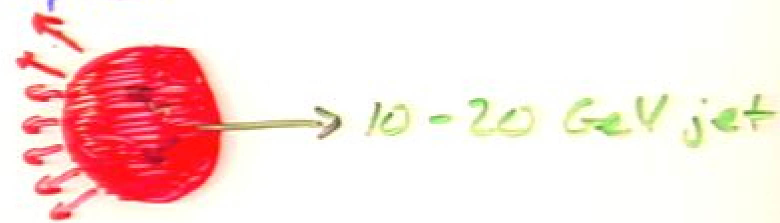
To what quantities does it apply?

- η/s?
- other suggestions on the QCD side relate to "jet quenching"....

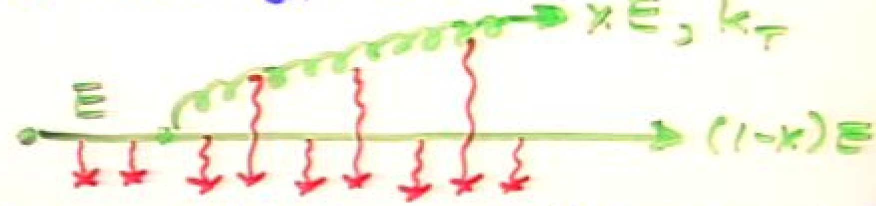
  [Could one study "atom quenching"??]

JET QUENCHING

Further evidence that QGP@RHIC is strongly coupled.



Radiative energy loss



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

If so (RHIC? LHC?), energy loss sensitive to medium through one 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 $\omega < \hat{q} L^2$

JET QUENCHING PARAMETER $\hat{q}$

- Assume $\gg k_T \gg T$
- Assume weak $\alpha_s(k_T)$.
  - $\therefore$ radiative energy loss
- If $\alpha_s(T)$ were weak,

$$\hat{q} \sim \frac{\mu^2}{\lambda} \quad \begin{matrix} \leftarrow \text{(Debye screening length)}^{-2} \\ \leftarrow \text{mean free path} \end{matrix}$$

$$\sim n_{\text{gluons}} \cdot \alpha_s^2$$

$$\simeq 3.1\, \alpha^2 N_c^2 T^3 \quad \text{Baier Schiff}$$

$$\simeq 0.9 \text{ GeV}^2/\text{fm} \quad (N_c = 3,\ \alpha = \tfrac{1}{2},\ T = 300\text{ MeV}$$

- BUT: smallness of η/s indicates QCD at scales $\sim T$ not weakly coupled
- AND: $\hat{q}$ extracted via comparison with RHIC data is
  - ~ 4-14 GeV^2/fm Dainese Loizides Paic
  - ~ 3 GeV^2/fm Zhang Owens Wang Wang
  - ~ 8-19 GeV^2/fm, at 2σ, neglecting theoretical uncertainty PHENIX
- WANTED: strong coupling calculation of $\hat{q}$

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  $\sim n_{gluons} \cdot \alpha_s^2$

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$\hat{q}$ IN $\mathcal{N}=4$ SYM

In $N_c^2 \to \infty$ $\lambda \to \infty$ limit,

$$\hat{q} = \frac{2\pi^2\,\Gamma(5/4)}{\Gamma(3/4)}\sqrt{\alpha N_c}\,T^3 = 27\sqrt{\alpha N_c}\,T^3$$

H Liu, KR, Wiedemann

- $\frac{1}{\lambda^{3/2}}$ corrections partially known, Armesto Edelstein Mas
  $1/N_c^2$ corrections not known.
- $\hat{q}$ is not proportional to S, or to $n_{\text{scatterers}}$. These are $\sim N_c^2 T^3$.
- Multiple gluon correlations are as important as two gluon correlations.
  Liang, Wang, Zhou
- Reminds us that liquids do not have well-defined quasiparticles, so should not expect $\hat{q}$ to count number density of such.
- Try some numbers: $N_c = 3$, $\alpha = 1/2$
  $\to \hat{q} = 5\ \text{GeV}^2/\text{fm}$ for $T = 300$ MeV
- In ballpark of what RHIC data wants

FROM $\hat{q}_{\mathcal{N}=4}$ TOWARDS $\hat{q}_{QCD}$

Examples of steps towards QCD on 2 "axes":

NUMBER OF DEGREES OF FREEDOM:

- For any CFT with a gravity dual,

$$\hat{q}_{CFT}/\hat{q}_{\mathcal{N}=4} = \sqrt{S_{CFT}/S_{\mathcal{N}=4}}$$ Liu KR Wiedemann

! further highlights lesson

- So, is $(\hat{q}/\sqrt{\lambda}T^3)/\sqrt{S/N_c^2T^3}$ universal like $\frac{\eta}{s}$??
- So, is $\hat{q}_{QCD}/\hat{q}_{\mathcal{N}=4} \sim \sqrt{47.5/120} = 0.63$??

NONCONFORMALITY:

- In one toy model, adding nonconformality to the degree indicated by lattice QCD calculations of thermodynamic measure of nonconformality $(\varepsilon-3P)/\varepsilon$

INCREASES $\hat{q}$ by 23% @ T=200 MeV

Liu KR Shi by 10% @ T=300 MeV

UPON TAKING THESE TWO STEPS:

Still in ballpark of what RHIC data wants

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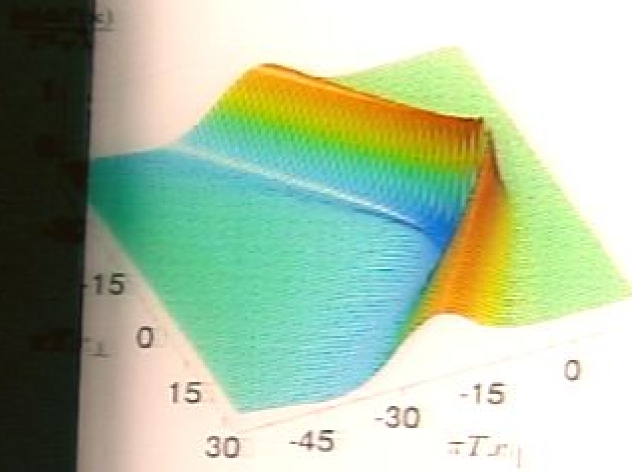
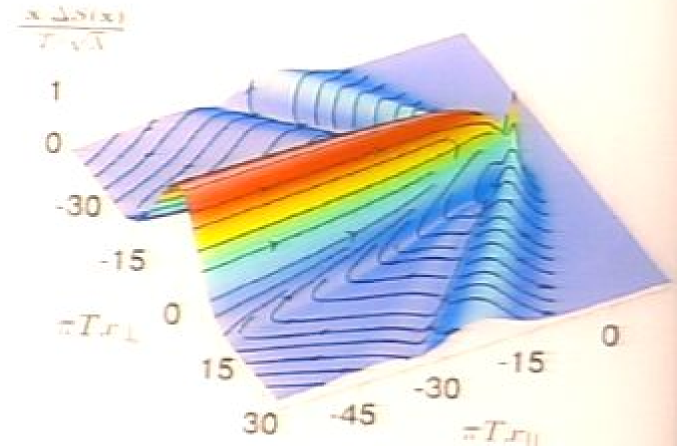




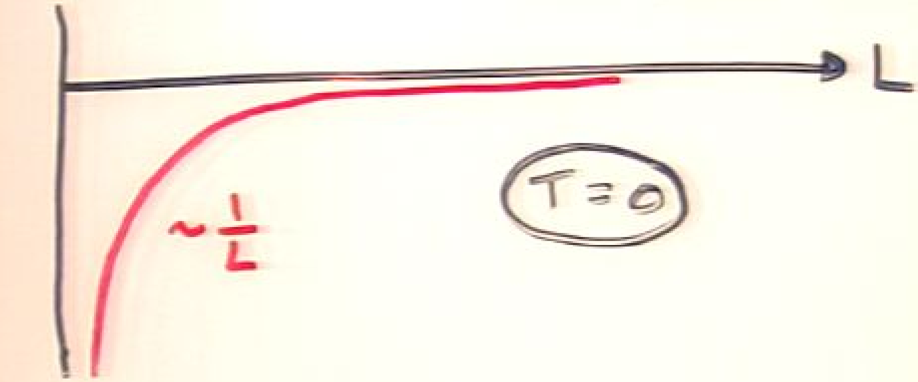
ergy density.
pecific heat $\propto N_c^2$ amplifies
of heat over motion in E.
s plot tells you where there
ting. Ie compression.
SOUND.

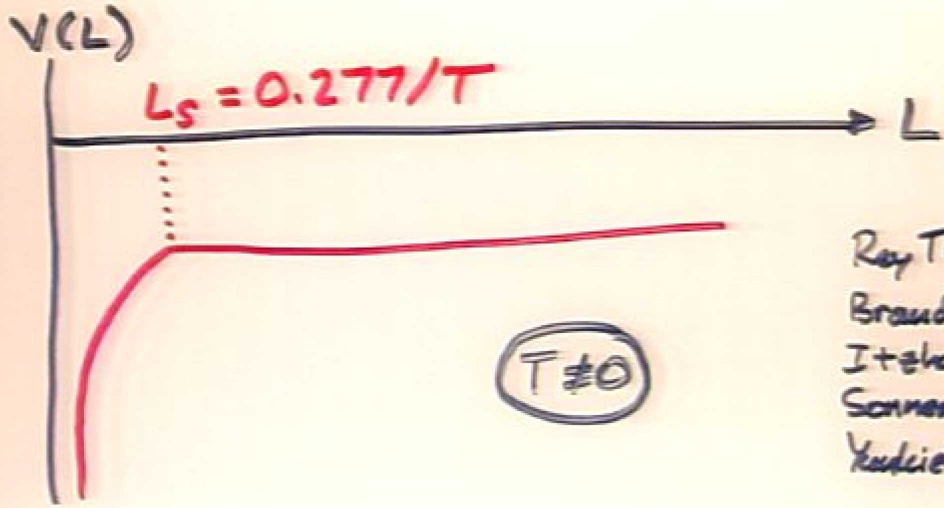
Momentum flow.
Mach cone and wake.

Chesler + Yaffe

SCREENING IN N=4

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



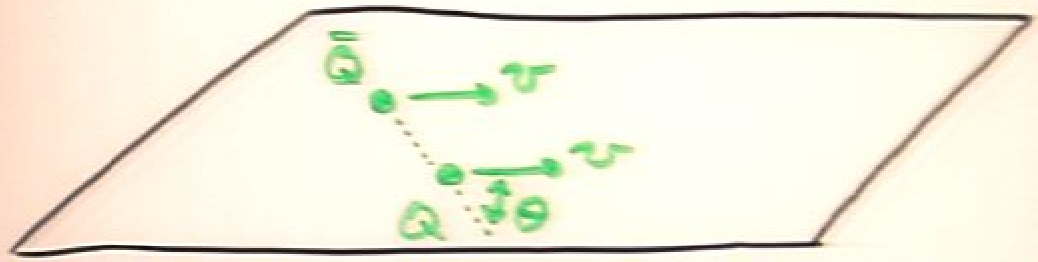


Rey Theisen Yee,
Brandhuber
Itzhaki
Sonnenschein
Yankielowicz

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

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:

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

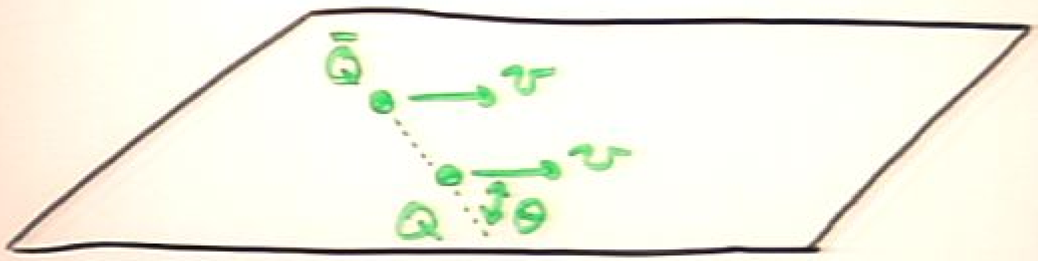
LRW; Peeters et al; Chernicoff et al; Caceres et al

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

- 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

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:

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

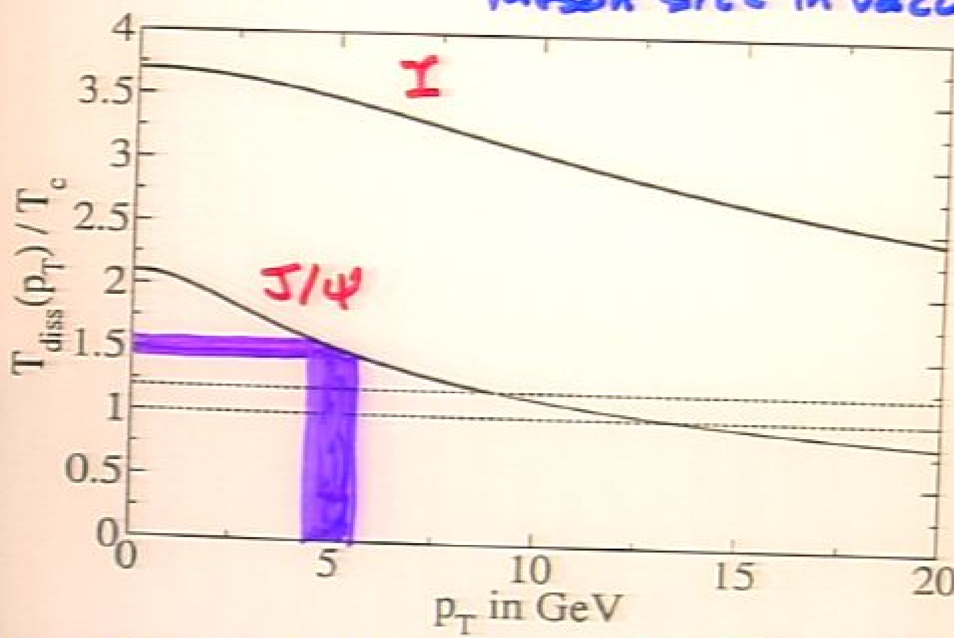
LRW; Peeters et al; Chernicoff et al; Caceres et al

where f is almost a constant. ($f(0,0)=$[illegible] $f(0,\frac{\pi}{2})=.743$)

- 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 $2.1\, T_c < T_{RHIC} < 1.2\, T_c$)

$\Rightarrow$ J/ψ <u>themselves</u> dissociate for

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

LIMITING VELOCITY FOR MESONS

Upon adding heavy quarks to $\mathcal{N}=4$ SYM, mesons ("quarkonia") Karch Katz; Babington et al; Kruczenski et al; Hoyos et al; .....
exist as bound states in the plasma only as long as $T < T_{diss}(v) = f(v)\, T_{diss}(0)/\sqrt{\gamma}$ Ejaz Faulkner Liu KR Wiedemann
with $1.01 < f(v) < .92$ for $0 < v < 1$.

→ AS INFERRED FROM STATIC POTENTIAL

GROWING MESON WIDTHS

These mesons have widths. [Myers Sinha @ $\mu \neq 0$; Liu Faulkner @ $\mu = 0$]
The widths blow up like k^2 beginning at a momentum k at which $v \sim v_{limiting}$, as inferred from static potential. Liu Faulkner

BARYON SCREENING

N_c quarks in a circle of radius L feel a potential when moving with velocity v only if $L < L_s^{baryon}(v) \simeq L_s^{baryon}(0)/\sqrt{\gamma}$

Athanasiou KR Liu

FURTHER CONFIRMATION OF ROBUSTNESS OF THE VELOCITY-DEPENDENCE OF SCREENING

INSIGHTS I DESCRIBED / SKETCHED

① Thermodynamics within 15-25% of that at zero coupling arises at strong coupling.

② $\eta/s = 1/4\pi$, in $N_c^2 \to \infty$, $\lambda \to \infty$ limit, for plasma of any gauge theory with a gravity dual. η/s in QCD plasma (lattice; RHIC) and for unitary cold atom gas seems comparable.

③ $\hat{q} \propto \sqrt{\frac{s}{N_c^2 T^3}} \sqrt{\lambda}\, T^3$ for an infinite class of strongly coupled plasmas. Jet quenching does not count gluons; all multiple gluon correlations equally important.

$\hat{q} \sim 3\text{-}5\ \mathrm{GeV}^2/\mathrm{fm}$ at $T = 300$ MeV. $\frac{\hat{q}_{LHC}}{\hat{q}_{RHIC}} \sim \frac{(dN/d\eta)_{LHC}}{(dN/d\eta)_{RHIC}}$

④ In a strongly coupled plasma, heavy POINT-LIKE quarks drag, diffuse, and excite a Mach cone.

⑤ Heavy quarkonia mesons, bound above T_c, dissociate at lower temperatures when moving. $T_{diss}(v) \simeq T_{diss}(0)\,(1-v^2)^{1/4}$

Also for heavy quark baryons.

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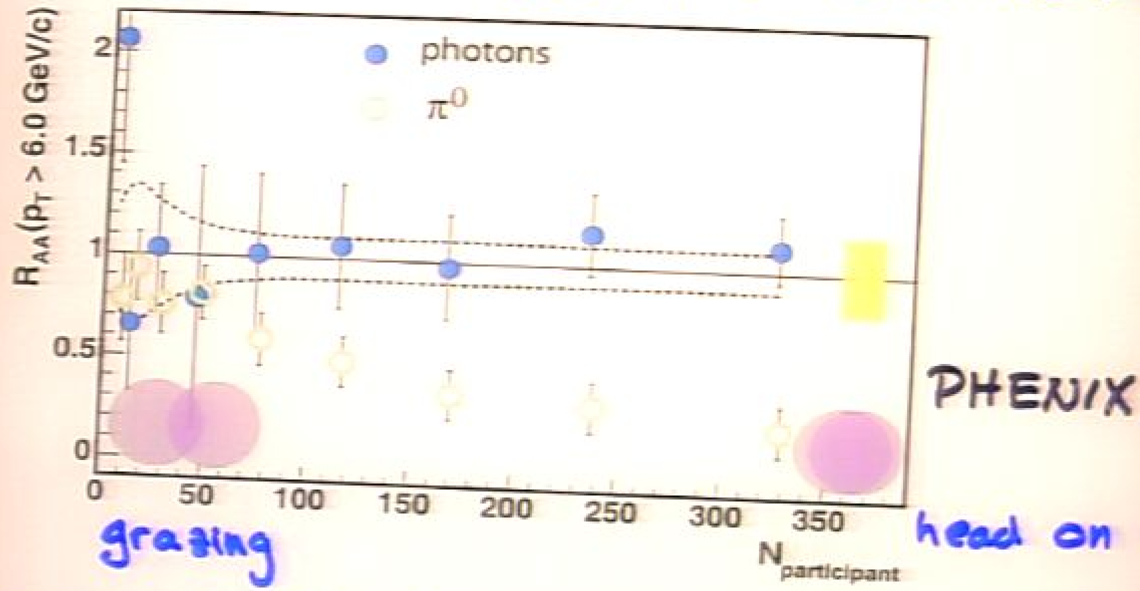
JET QUENCHING, III

CONTROL EXPERIMENT: 6 GeV pions are missing
6 GeV photons shine through



$R_{AA} = \dfrac{\text{\# seen in Au-Au collision}}{\text{\# expected if just independent p-p collisions}}$