INSIGHTS

INTO

STRONGLY COUPLED

PLASMAS

VIA

AdS/CFT

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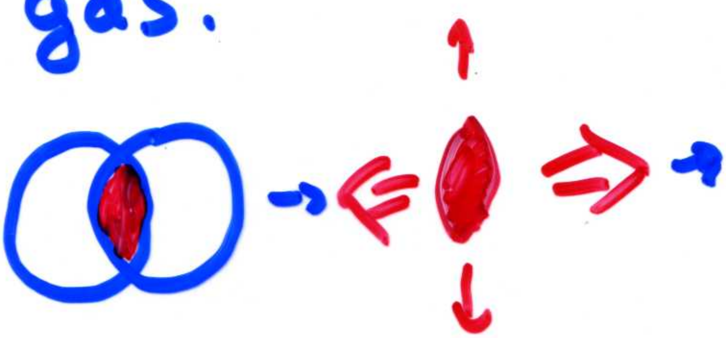
(MIT)

QUARK MATTER 2008, JAIPUR

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.)

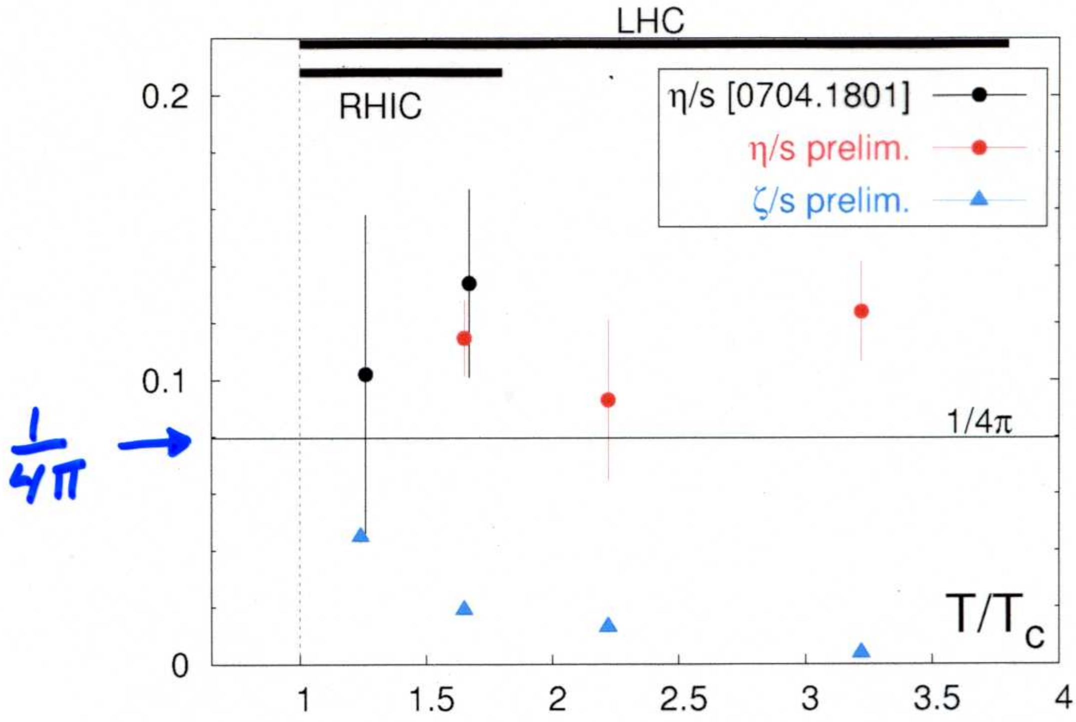
→ $\frac{\text{shear viscosity}}{\text{entropy density}} = \frac{\eta}{s} < \mathcal{O}(0.1)$

[> 0.2 ruled out]

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

$\eta/s \sim 10$ in water

LATTICE CALCULATION OF η/s & ζ/s IN $N_f = 0$ QCD

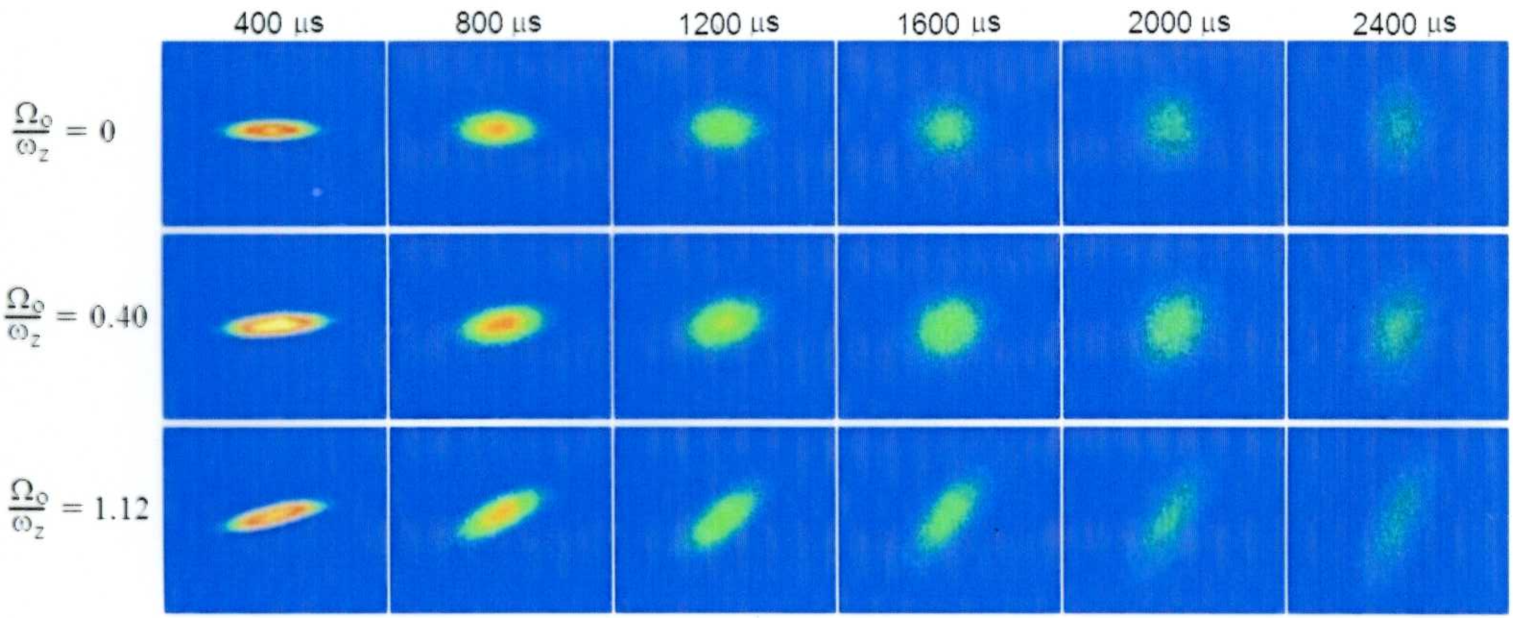


$N_\tau = 8 \quad N_f = 0$ Harvey Meyer '07

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

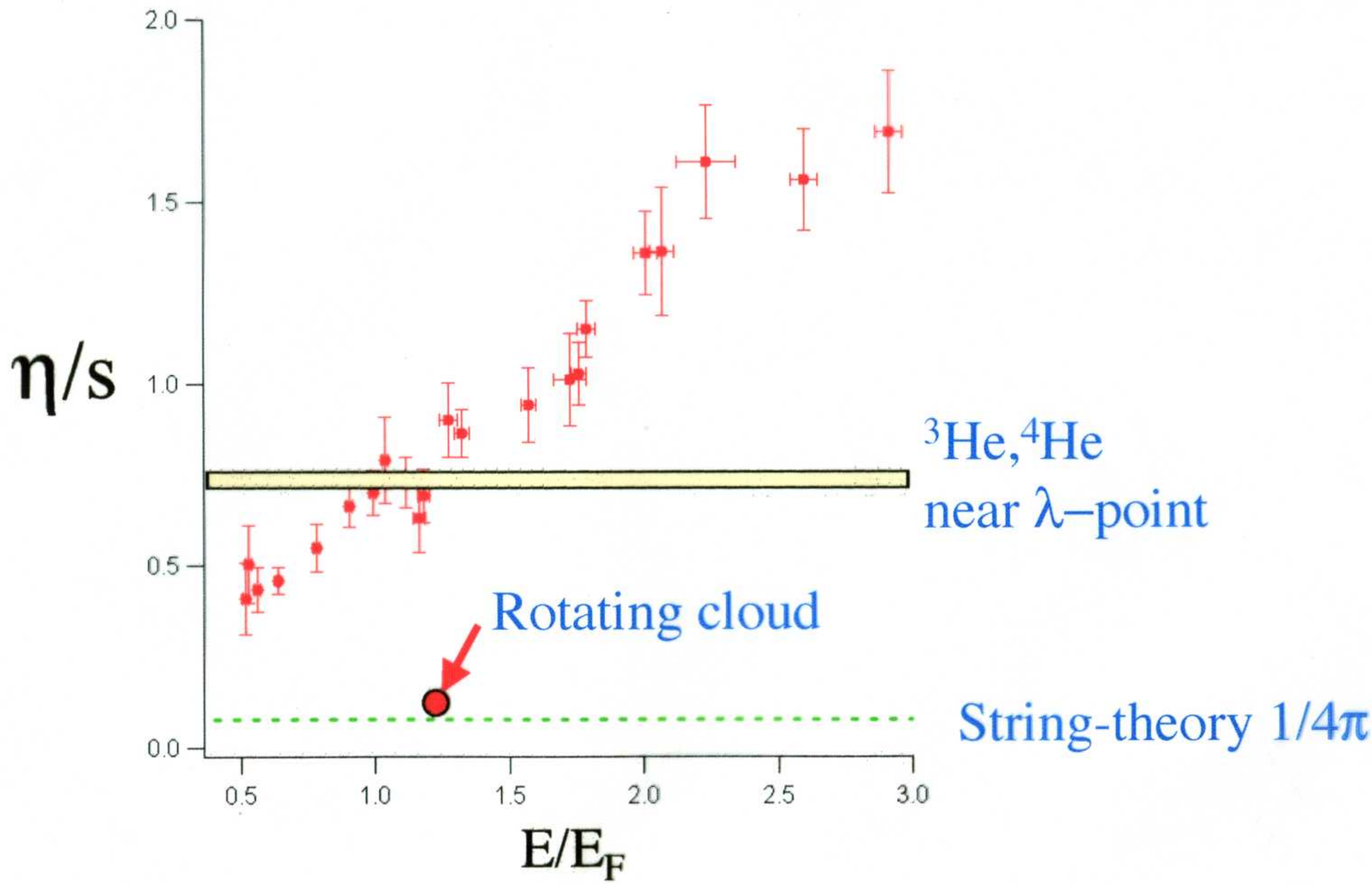
Expansion of a rotating strongly interacting Fermi gas

Duke Physics
Atom Cooling and Trapping



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

Duke Physics
Atom Cooling and Trapping



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?

$\mathcal{N}=4$ 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 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 those insights are done. I am happy to do so privately for any of you. <u>All</u> of them are easy enough to be done by undergraduates, once you learn the rules.

THERMODYNAMICS

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

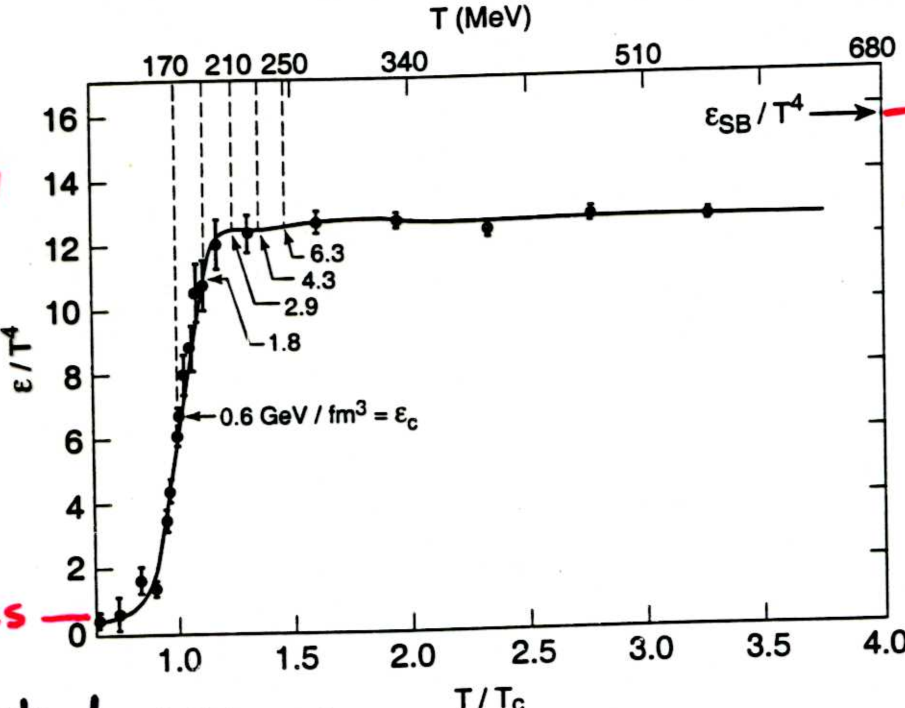
$$\frac{\varepsilon_{\lambda=\infty}}{\varepsilon_{\lambda=0}} = \frac{P_{\lambda=\infty}}{P_{\lambda=0}} = \frac{S_{\lambda=\infty}}{S_{\lambda=0}} = \frac{3}{4}$$

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

T(MeV), assuming $T_c = 170$ MeV.
(estimate is $140 < T_c < 190$)

$\frac{\varepsilon}{T^4}$



— ideal QGP

pion gas —

DECONFINEMENT

(IONIZING THE HADRONS)

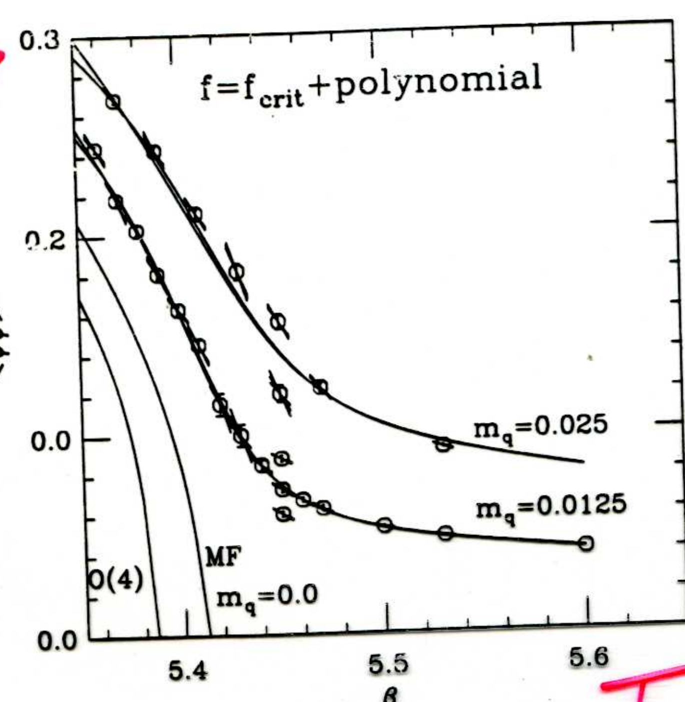
Karsch Laermann Peikert (Heinz)

T/T_c

&

$\langle \bar{\psi}\psi \rangle$

Blum DeTar MILC collab.



CHIRAL SYMMETRY RESTORATION (MELTING THE VACUUM) ON THE LATTICE

$N_f = 2$
$m_q \neq 0$
∴ smooth crossover

T
(funny units)

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?

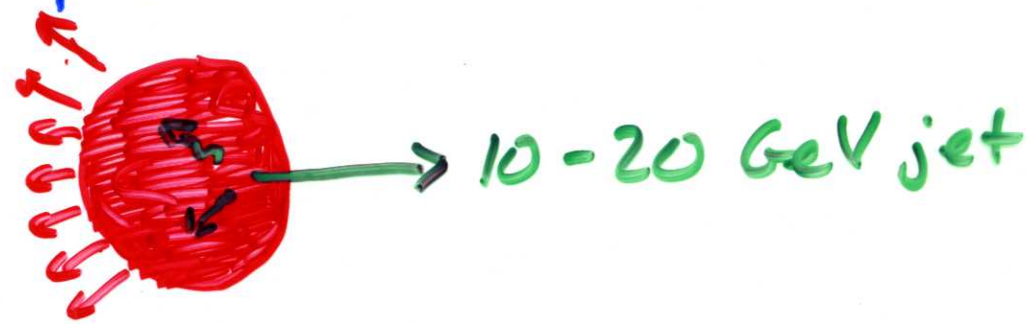
- quark-gluon plasma dual to string theory + black hole?
- QCD quark-gluon plasma?
- unitary fermionic atom gas?

To what quantities does it apply?

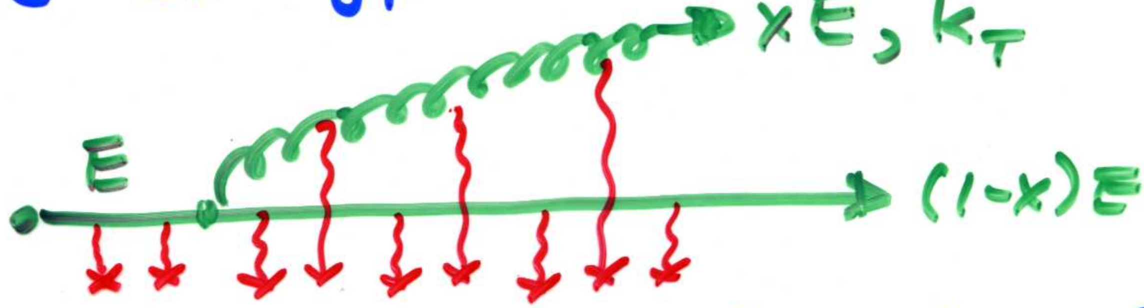
- η/s ?
- other suggestions on the QCD side relate to "jet quenching"..... Could you study "atom quenching"?

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 $E \gg k_T \gg T$
- Assume <u>weak</u> $\alpha_s(k_T)$.

  $\therefore$ radiative energy loss

- If $\alpha_s(T)$ were weak,

$$\hat{q} \sim \frac{\mu^2}{\lambda}$$

  μ^2 ← (Debye screening length)$^{-2}$

  λ ← mean free path

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

$$\simeq 3.1\, \alpha^2 N_c^2 T^3$$ Baier Schiff

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

- BUT: smallness of η/s indicates QCD at scales $\sim T$ <u>not</u> weakly coupled
- AND: $\hat{q}$ extracted via comparisom with RHIC data is

  $\sim$ 4-14 GeV^2/fm Dainese Loizides Paic

  $\sim$ 3 GeV^2/fm Zhang Owens Wang Wang

  $\sim$ 8-19 GeV^2/fm, at 2σ, neglecting theoretical uncertainty PHENIX

- WANTED: strong coupling calculation of $\hat{q}$

$\hat{q}$ 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 <u>not</u> proportional to s, or to $n_{scatterers}$. 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: $N_c = 3$, $\alpha = 1/2$
  $\rightarrow \hat{q} = 5\ \mathrm{GeV^2/fm}$ for $T = 300$ MeV
- In ballpark of what RHIC data wants....

TOWARDS QCD

- For any CFT with a gravity dual,

$$\frac{\hat{q}_{CFT}}{\hat{q}_{\mathcal{N}=4}} = \sqrt{\frac{s_{CFT}}{s_{\mathcal{N}=4}}}$$

Liu KR Wiedemann

further highlighting the lesson.

- Is $\dfrac{\hat{q}/\sqrt{\lambda}}{\sqrt{s/N_c^2}}$ universal like η/s ?

Not known....

- Also suggests

$$\frac{\hat{q}_{QCD}}{\hat{q}_{\mathcal{N}=4}} \sim \sqrt{\frac{47.5}{120}} \sim 0.63$$

- In one toy model, adding nonconformality (to a degree indicated by QCD thermo.) increases $\hat{q}$ by 22% at $T = 200$ MeV
9% at $T = 300$ MeV.

Liu KR Shi

- Still in ballpark of what RHIC data wants...

A PREDICTION FOR LHC

If we assume $\sqrt{\alpha_{LHC}} \sim \sqrt{\alpha_{RHIC}}$ then $\hat{q} \sim T^3$. This, plus Bjorken expansion, yields:

$$\frac{\bar{\hat{q}}_{LHC}}{\bar{\hat{q}}_{RHIC}} = \frac{(dN/d\eta)_{LHC}}{(dN/d\eta)_{RHIC}}$$

Liu KR Wiedemann

where
$$\bar{\hat{q}} \equiv \frac{2}{L^2}\int_0^L d\tau\, \tau\, \hat{q}(\tau)$$

is the time averaged $\hat{q}$ which determines parton energy loss and is extracted by comparison with data.

MOVING HEAVY QUARKS: DRAG AND DIFFUSION

For a quark with mass M moving through the plasma with velocity v such that $M > \frac{\sqrt{\lambda}\, T}{(1-v^2)^{1/4}}$ or $\frac{1}{(1-v^2)^{1/4}} < \frac{M}{\sqrt{\lambda}\, T}$

energy loss occurs via drag and diffusion:

$$\frac{dp}{dt} = -\eta_{Drag}\, p + \xi(t), \quad \langle \xi(t), \xi(t') \rangle = \kappa\, \delta(t-t')$$

where $\eta_{Drag} = \frac{\pi \sqrt{\lambda}\, T^2}{M}$ and $D = \frac{2T^2}{\kappa} = \frac{2}{\pi T \sqrt{\lambda}}$

Herzog Karch Kovtun Kozcaz Yaffe; Gubser; Casalderrey-Solana Teaney; ...

- This D, in the Langevin formalism of Moore + Teaney, yields R_{AA} and v_2 for heavy quarks in broad agreement with RHIC data for non-photonic electrons.

WHERE DOES THE ENERGY GO?

For a heavy quark with $v > v_{sound} = 1/\sqrt{3}$

but $\dfrac{1}{(1-v^2)^{1/4}} < \dfrac{M}{\sqrt{\lambda}\, T}$

through the strongly coupled plasma of $\mathcal{N}=4$ SYM, we now know:

- Mach cone
- and wake

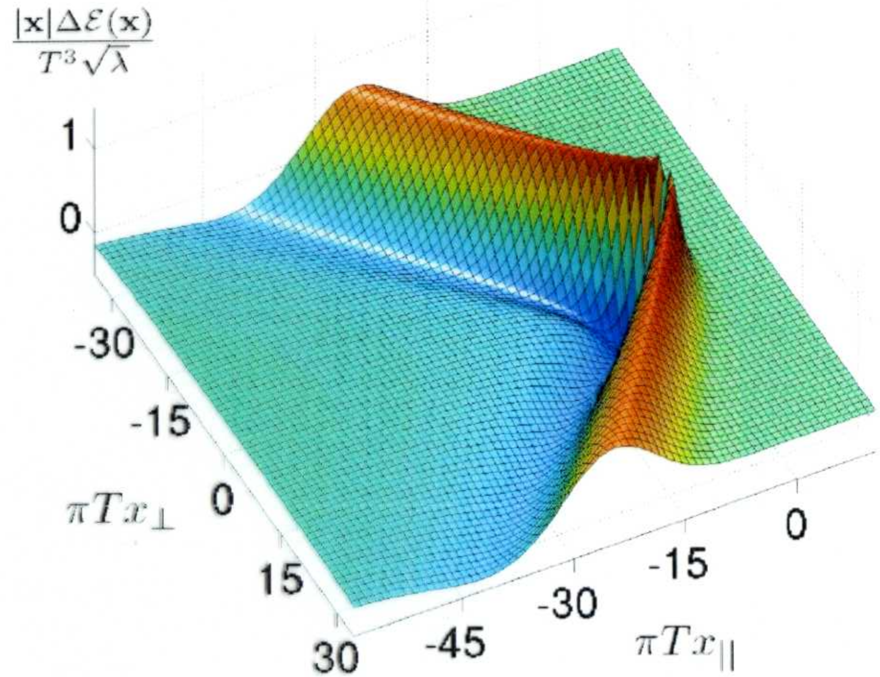
Friess Gubser Michalogiorgakis Pufu Yarom; Chesler Yaffe; Noronha Torrieri Gyulassy; ...
↳ Parallel talk today

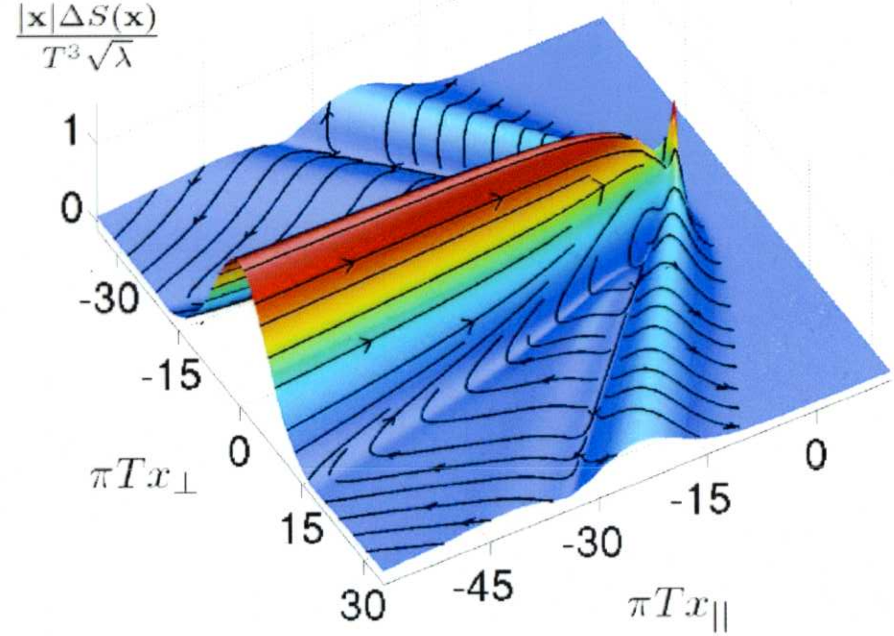
with relative strengths such that, according to hydrodynamic calculations with Cooper-Frye freezeout, the Mach cone should be considerably filled in in the data.

Casalderrey-Solana Shuryak Teaney

- BUT: a point particle does make a Mach cone
- Remarkably similar cone + wake for point quark, with its color field, moving through QCD QGP, assuming small η.

B. Müller, parallel talk on Friday





Energy density.

Nb: Specific heat ∝ N_c^2 amplifies effect of heat over motion in $\mathcal{E}$. So, this plot tells you where there is heating. Ie compression. Ie SOUND.

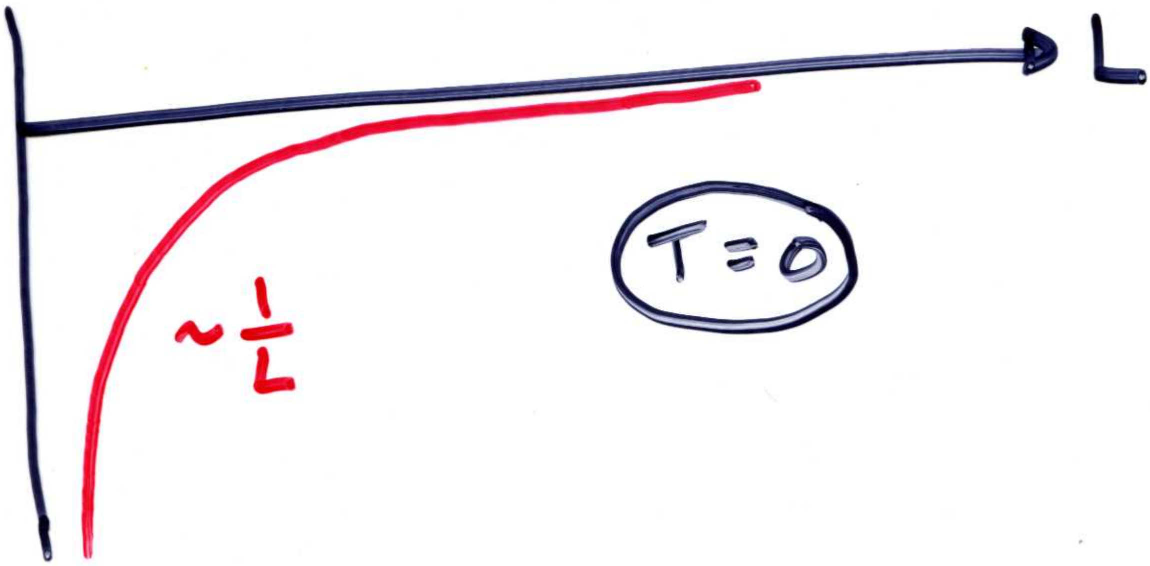
Momentum flow.

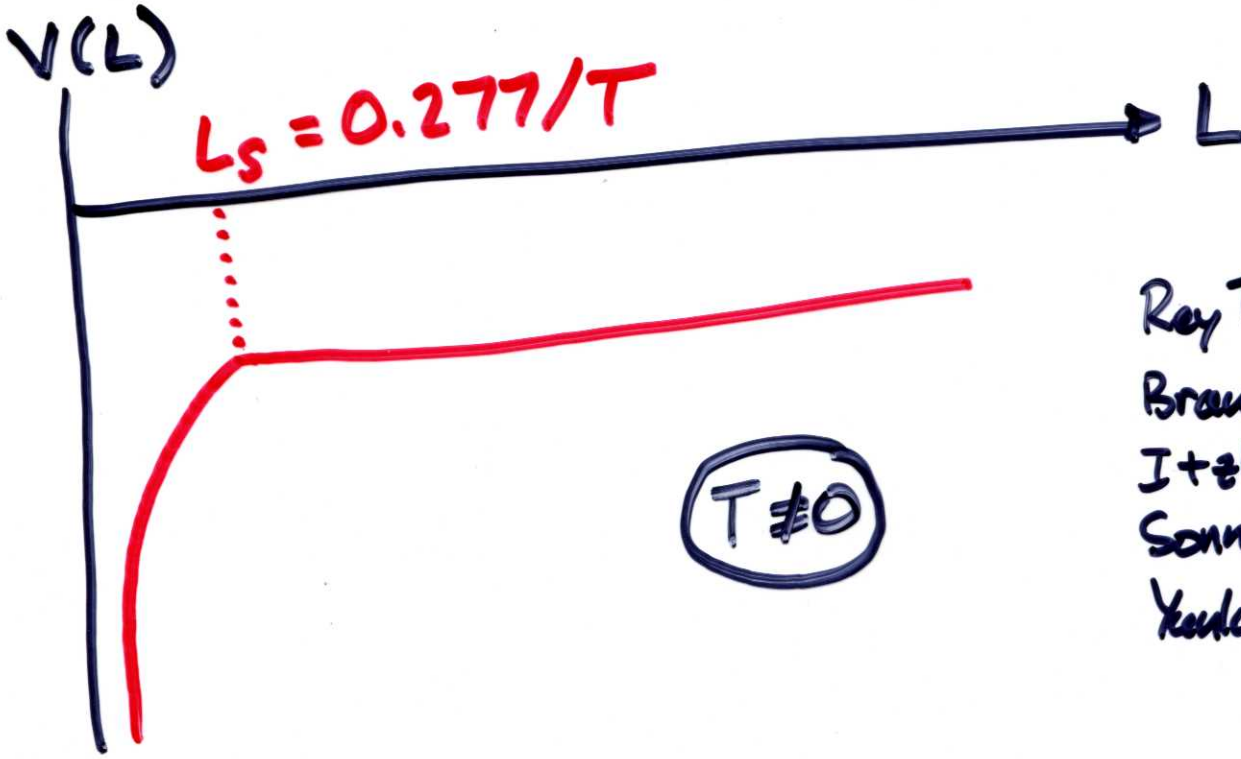
Mach cone and wake.

Chesler + Yaffe

SCREENING IN N=4

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

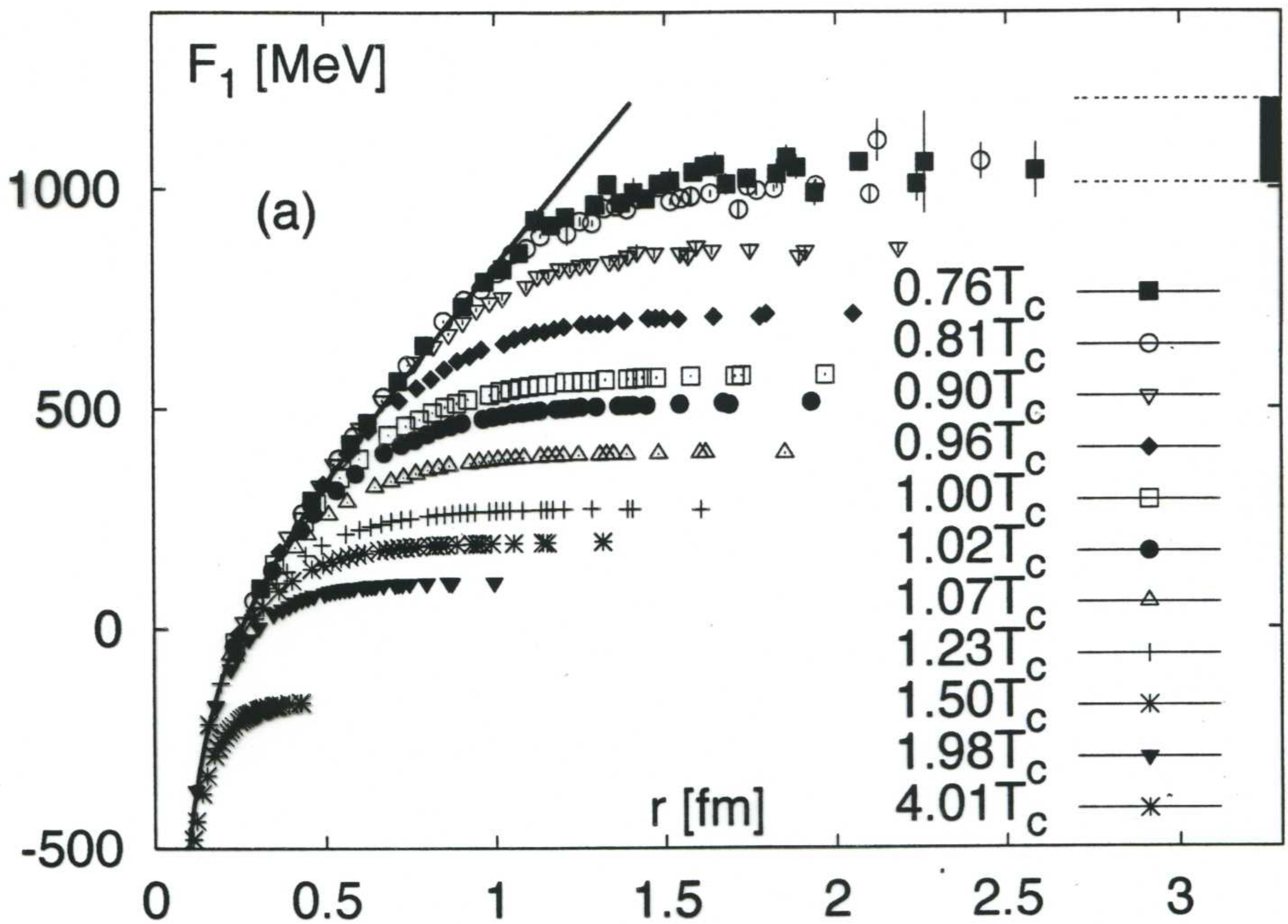




Rey Theisen Yee;
Brandhuber
Itzhaki
Sonnenschein
Yankielowicz

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

SCREENING IN QCD



Kaczmarek, Zantow

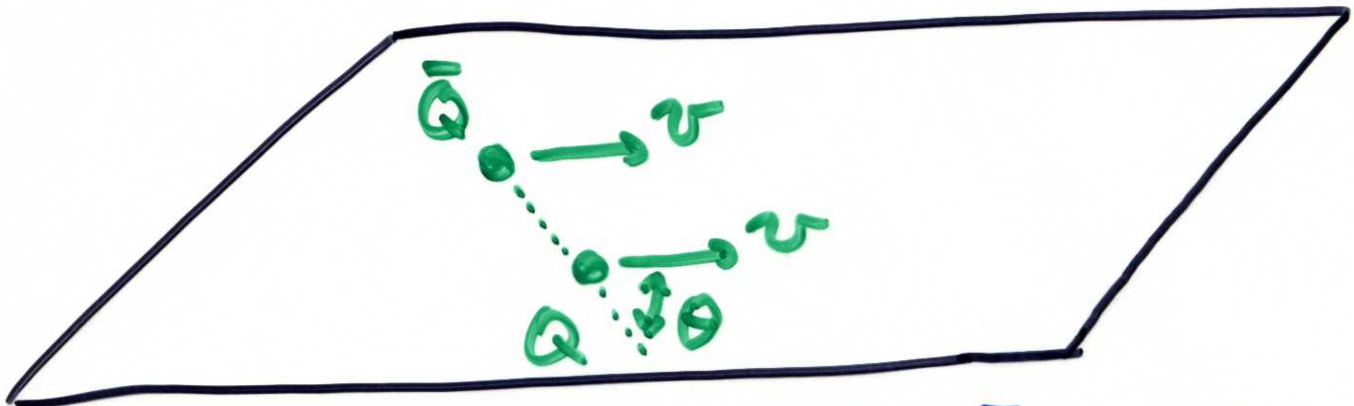
lattice QCD calculation

[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:

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

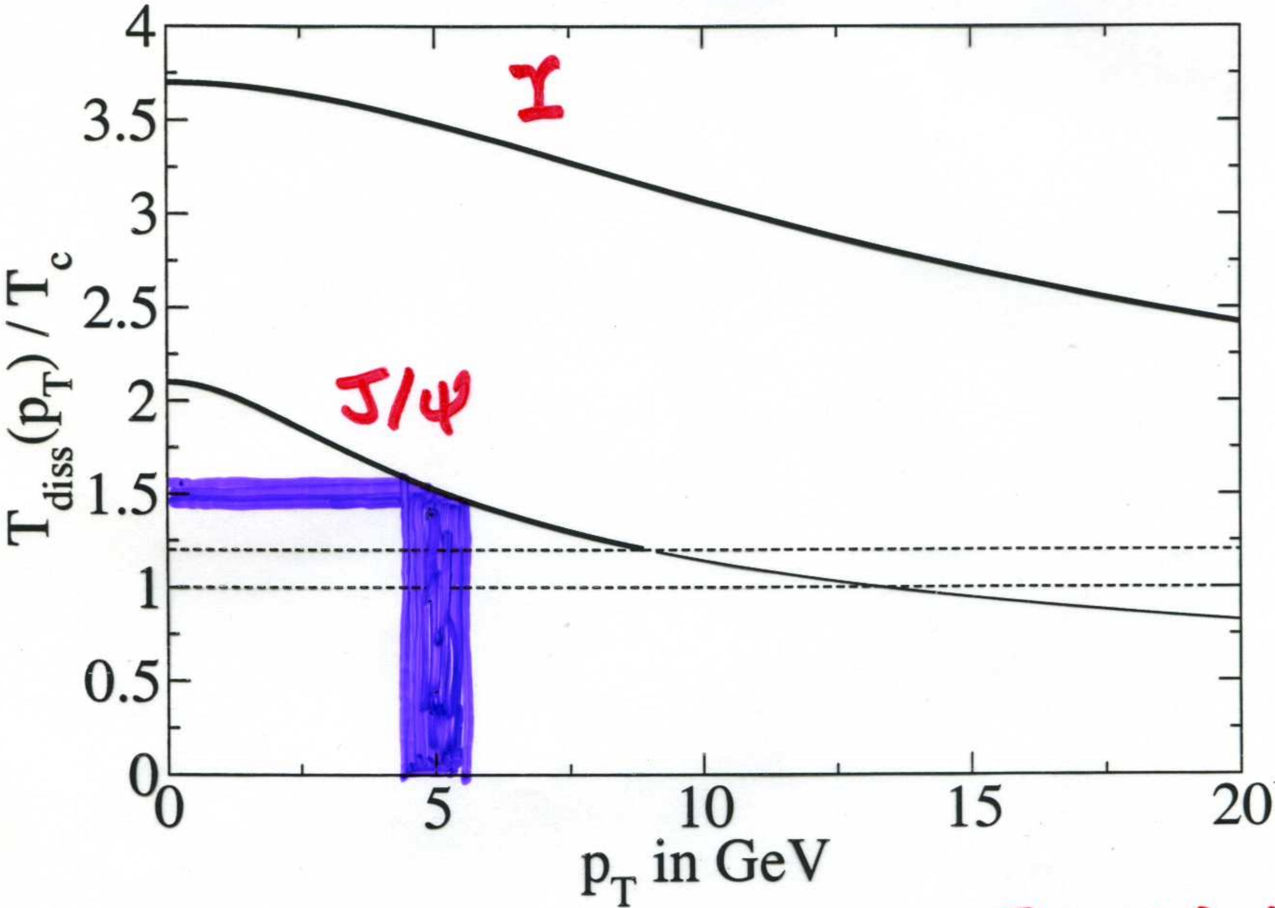
LRW; Peeters et al; Chernicoff et al; Caceres et al

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

$\Rightarrow$ J/ψ themselves dissociate for

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

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

Hot-wind scenario in hydro+J/ψ model

T. Gunji, H. Hamagaki, T. Hatsuda, T. Hirano, Y. Akamatsu : Phys. Rev. C 76:051901 (R), 2007
Parallel talk at QM2008 by T. Gunji , Feb. 9th SessionXVIII 15:20~15:40

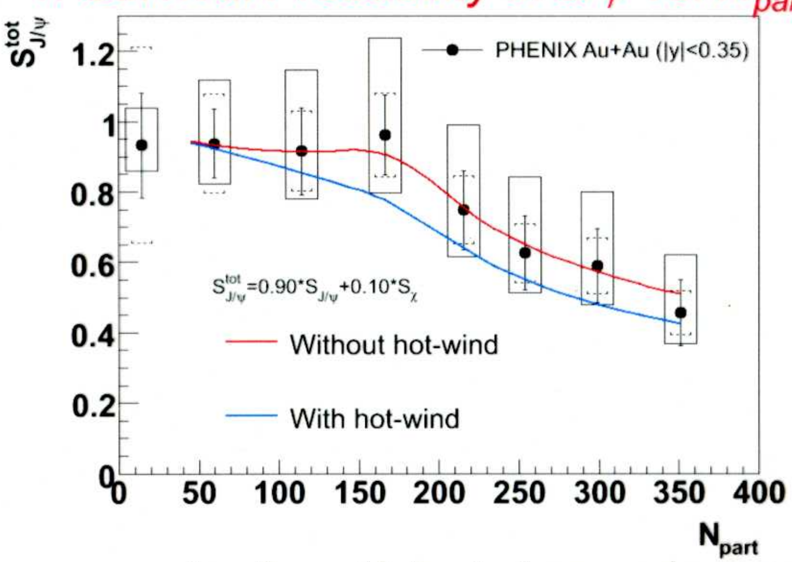
Melting temperature in hot-wind

$$T_{melt}(v) = T_{melt}(0)(1-v^2)^{1/4}$$

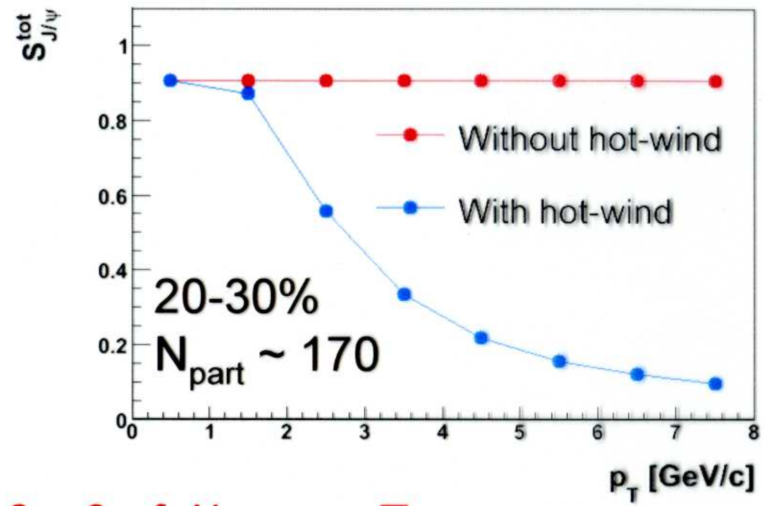
H. Liu et al. PRL.98:182301,2007

Melting temperatures : $(T_{J/\psi}, T_{\chi}) = (2.0T_c, 1.34T_c)$
10% feed-down correction

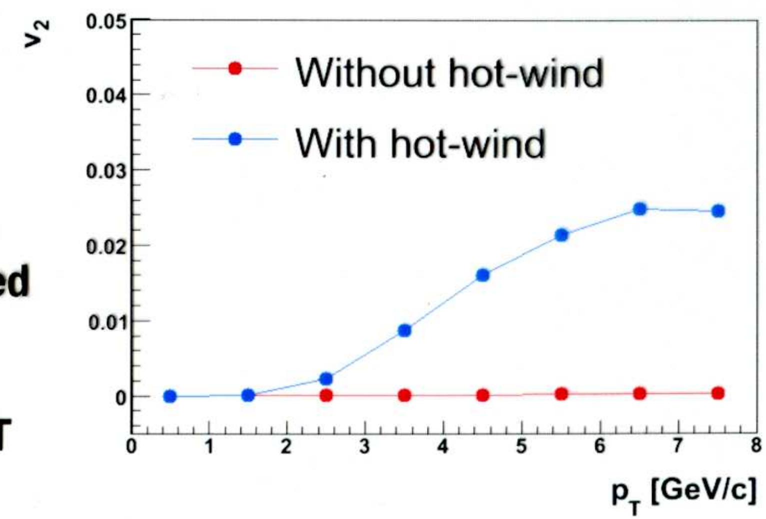
1: Survival Probability of J/ψ vs. N_{part}



2: Survival Probability of J/ψ vs. pT



3: v2 of J/ψ vs. pT



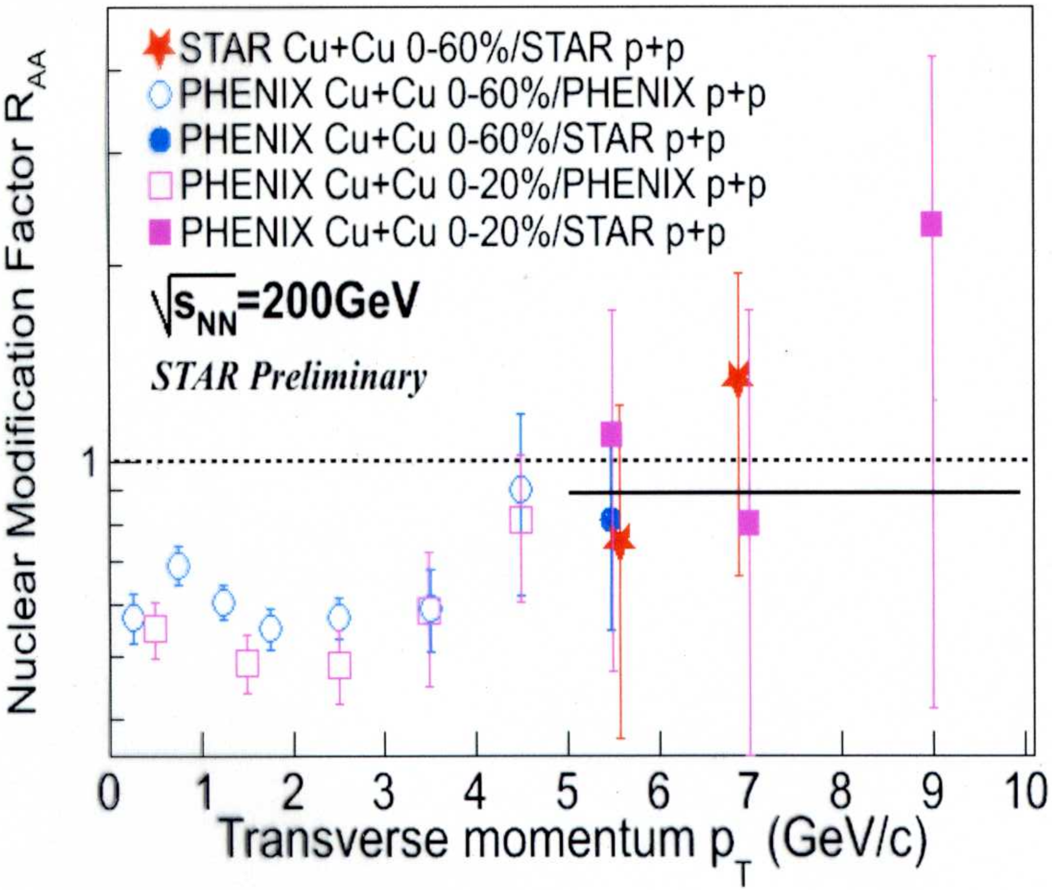
- J/ψ suppression from Hot-wind scenario was calculated in hydro+J/ψ model.
- Overall suppression pattern is similar in both cases.
- Larger suppression and large v2 (~3%) in the high pT region in a scenario with hot-wind.

- Gunji et al show that the reduction in T_{diss} for J/ψ's that feel a hot wind is:
  - a small effect in $S^{tot}_{J/\psi}$
  - significant in $S^{p_T}_{J/\psi}$
  - p_T at which effect sets in is:
    - sensitive to, and thus a measure of,

      $T_{diss}(v=0) - T_{reached}$

      [Increasing $T_{diss}(v=0)$ from 2.0 to 2.2 GeV pushes this p_T up to 4-5 GeV]
    - and, ∴, higher in Cu-Cu than AuAu
- $R^{J/\psi}_{AA}(p_T)$ will be interesting to watch as error bars come down
- Υ'/Υ vs. p_T (eg at LHC) [or $\psi'/J/\psi$] even better since any p_T-dependence of $b+\bar{b}$ ($c+\bar{c}$) production [eg Cronin; eg regeneration; eg gluon en. loss;...] cancels

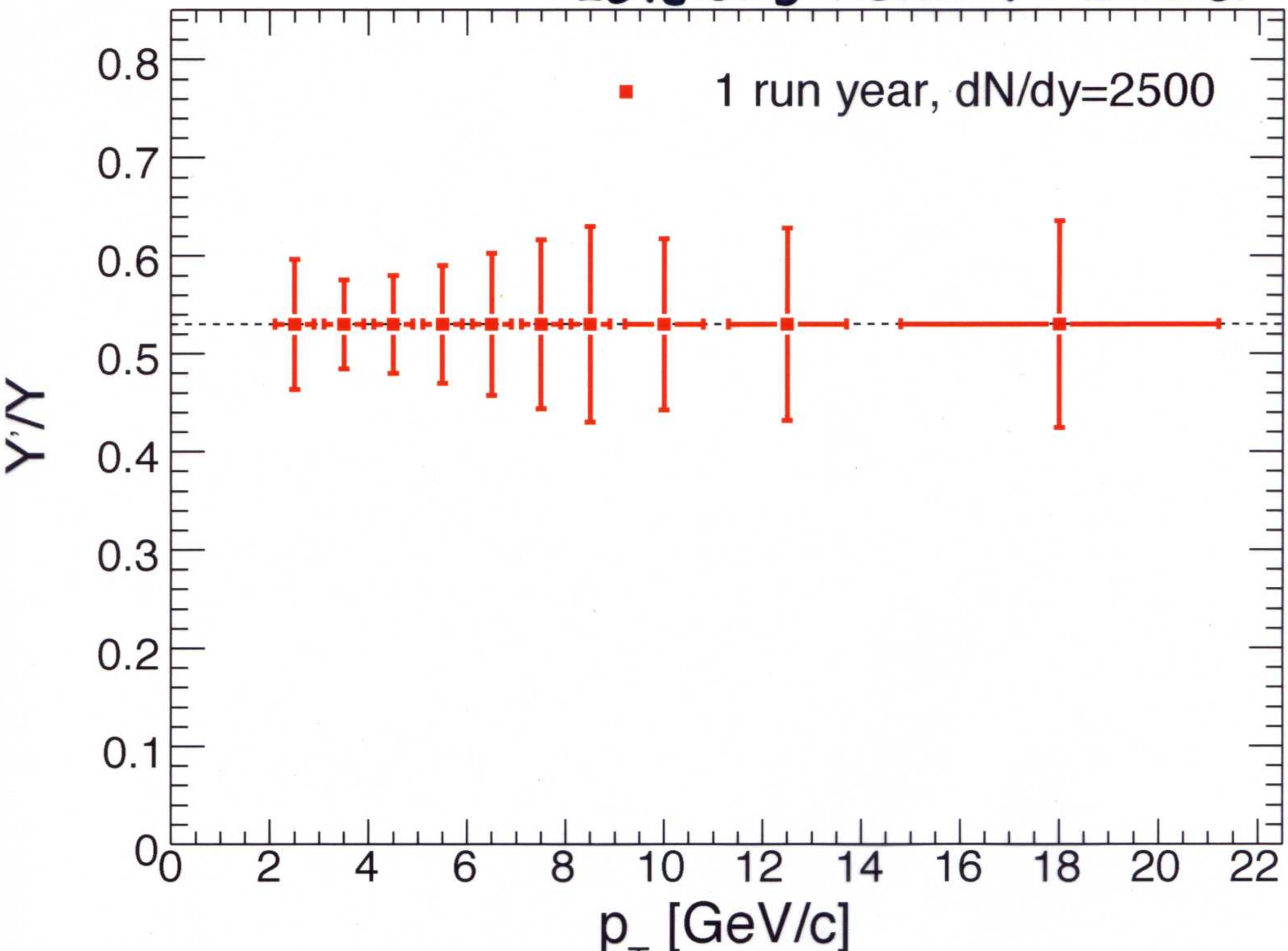
Nuclear modification factor R_{AA}



- Double the p_T range to 10GeV/c
- Consistent with no suppression at high p_T:
  $R_{AA}(p_T>5$ GeV/c$) = 0.89\pm0.20$
- Indicates R_{AA} increase from low p_T to high p_T
- Different from expectation of most models:
  AdS/CFT:
  H. Liu, K. Rajagopal and U.A. Wiedemann, PRL 98, 182301(2007) and hep-ph/0607062
  Two Component Approach:
  X. Zhao and R. Rapp, hep-ph/07122407

Υ′/Υ RATIO AT CMS@LHC

Loizides Roland Roland



Suppose $T \sim 3T_c$. Then, Υ unaffected for $p_T \lesssim 10$ GeV, dissociated for $p_T \gtrsim 10$ GeV. Expect Υ′ dissociated at any p_T.

MESONS

Parallel talk today by A. Sinha

Upon introducing dynamical, but heavy, quarks into $\mathcal{N}=4$ SYM, mesons ("quarkonia") exist as bound states in the plasma as long as

Karch Katz
Babington et al
Kruczenski et al
Mateos et al

$$T < T_{diss}(v) = f(v) \frac{T_{diss}(0)}{\sqrt{\gamma}}$$

Ejaz
Faulkner
Liu KR
Wiedemann

with $1.01 < f(v) < 0.92$ for $0 < v < 1$.

Justifies inference drawn from static potential

BARYON SCREENING

N_c quarks in a circle of radius L feel a potential only if

Athanasiou
Liu KR

$$L < L_s^{baryon}(v) = L_s^{baryon}(0)/\sqrt{\gamma}.$$

Further confirmation of robustness of the velocity-dependence of screening...

FROM $\mathcal{N}=4$ SYM TO QCD

- The two theories differ on various "axes". (But, much more similar at $T\neq 0$ than $T=0$)
- To make insights semiquantitative for QCD, need to take steps toward QCD on each such axis, & see how results change.
- Degrees of freedom at weak coupling differ: Define ν by $\varepsilon = \nu \frac{\pi^2}{30} T^4$

  Then: $\nu_{QCD} = 2(N_c^2-1) + \frac{21}{2} N_c = 47.5$ (for $N_c=3$)

  $\nu_{\mathcal{N}=4} = 15(N_c^2-1) = 120$ (for $N_c=3$)

  $\Rightarrow$ Need observables that are insensitive to this. (Eg η/s. Eg, perhaps, $\dfrac{\hat{q}}{\sqrt{\nu/N_c^2}}$.)

  NB: liquids have no quasiparticles anyway

- $\mathcal{N}=4$ calculations easy when $\lambda = g^2 N_c = 4\pi\alpha N_c \gg 1$. Leading corrections ($\sim 1/\lambda^{3/2}$) computed for η/s, and small; partially computed for $\hat{q}$.

- $\mathcal{N}=4$ is conformal. QCD is not.
  - But, for $2T_c < T < ?$, QGP thermodynamics is quite conformal [$\varepsilon \sim T^4$; $P \sim T^4$; $s \sim T^3$; $v_s^2 \simeq \frac{1}{3}$] and early indications from lattice are that $\eta/s \sim$ const and $\zeta/s \sim$ small.
  - So, perhaps strongly coupled QGP of QCD well-modelled as conformal
  - In studies to date, adding a level of nonconformality as in QCD thermodynamics to $\mathcal{N}=4$ SYM has <u>no</u> effect on η/s, little effect on $\hat{q}$.
- $\mathcal{N}=4$ calculations tractable when $1/N_c^2 \ll 1$. Leading $1/N_c^2$ corrections to any of quantities in this talk not currently known.

WHAT IS $g^2 N_c$ IN QGP@RHIC?

Need a quantity that is calculable at strong coupling in QCD, at finite $\lambda \equiv g^2 N_c$ in $\mathcal{N}=4$ SYM, and that does not depend on # of degrees of freedom.

Two examples, one classic, one new:

- $\dfrac{\varepsilon}{\varepsilon_{\text{noninteracting}}} = 0.78 - 0.82$ (Lattice QCD)

  cf: $= \dfrac{3}{4} + 1.69\,\lambda^{-3/2}$ ($\mathcal{N}=4$ SYM)

  $\rightarrow 9 < \lambda < 15$

- $\dfrac{\eta}{s} = .134(33)$ at $T = 1.65\,T_c$ (Lattice QCD)

  $= .102(56)$ at $T = 1.24\,T_c$ Meyer

  cf: $= \dfrac{1}{4\pi}\left(1 + 20.3\,\lambda^{-3/2}\right)$ ($\mathcal{N}=4$ SYM)

  $\rightarrow \eta/s = .134 \leftrightarrow \lambda = 10$

  $= .102 \leftrightarrow \lambda = 17$

INSIGHTS I DID NOT HAVE TIME TO DESCRIBE

include those arising from investigations of:

- Time-dependent backgrounds with gravity duals. (As opposed to dynamical probes of eqbm plasma.)
  Nastase; Shuryak Sin Zahed; Janik Peschanski; Nakamura Sin; Lin Shuryak; Friess Gubser Michalogiorgakis Pufu; Kajantie Tahkokallio Louko;...
  → Parallel talk by Shu Lin this afternoon
- DIS off $\mathcal{N}=4$ QGP Hatta Iancu Mueller
  → Parallel talk by Edmond Iancu this afternoon
- "photon" and "dilepton" emission from $\mathcal{N}=4$ QGP Caron-Huot Moore Kovtun Starinets Yaffe
- Magnetic description of $\mathcal{N}=4$ SYM plasma
  Liao Shuryak
  → Parallel talk by Jinfeng Liao this afternoon
- Meson spectral functions Son Starinets; Kovtun Starinets; Teaney; Myers Starinets Thomson; Myers Sinha;...

⋮

→ Parallel talk by Aninda Sinha this afternoon

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. $\hat{q} \sim 3$-$5\ \mathrm{GeV}^2/\mathrm{fm}$ 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.