SOME INSIGHTS INTO STRONGLY COUPLED PLASMA FROM AdS/CFT

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Workshop on NONPERTURBATIVE METHODS IN STRONGLY COUPLED GAUGE THEORIES

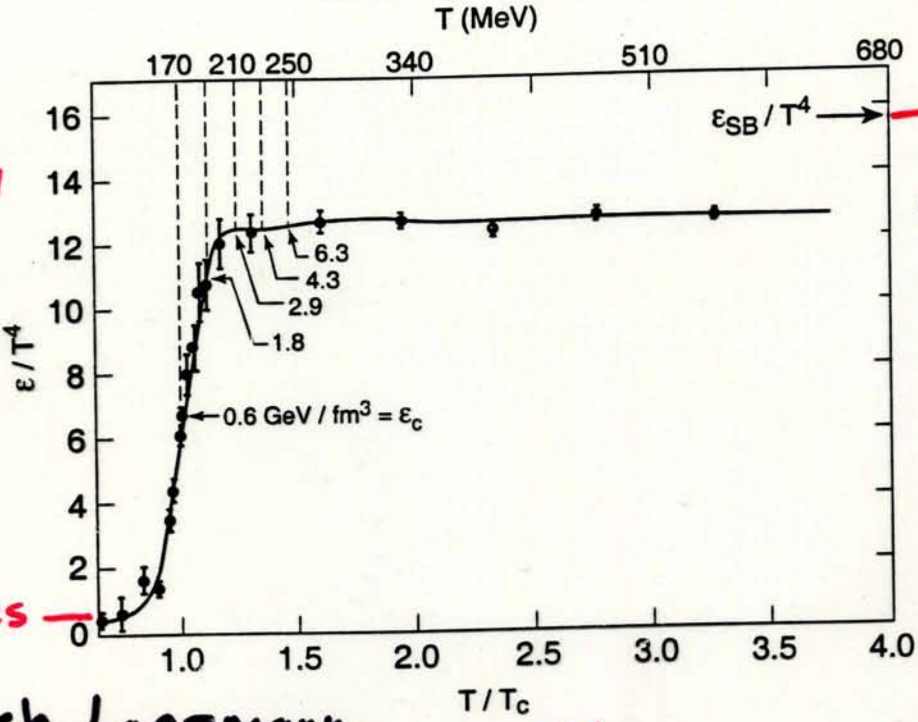
GALILEO GALILEI INSTITUTE
FLORENCE, ITALY
6/25/2008

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....

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

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



— ideal QGP

pion gas —

Karsch Laermann Peikert (Heinz)

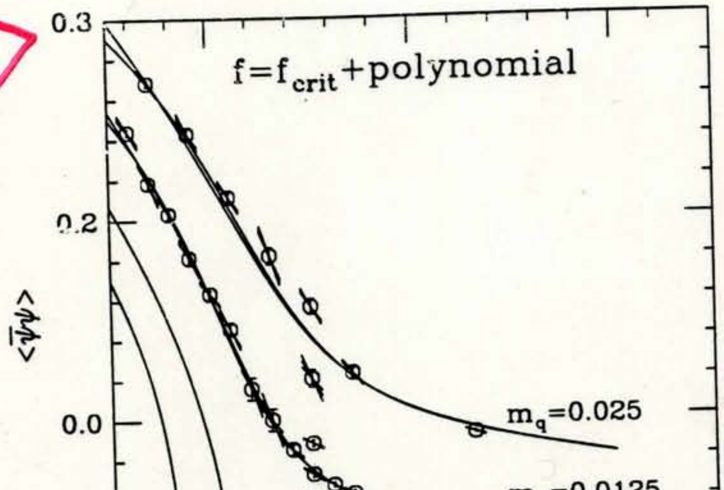
T/T_c

DECONFINEMENT
(IONIZING THE HADRONS)

&

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

Blum
DeTar
MILC
collab.

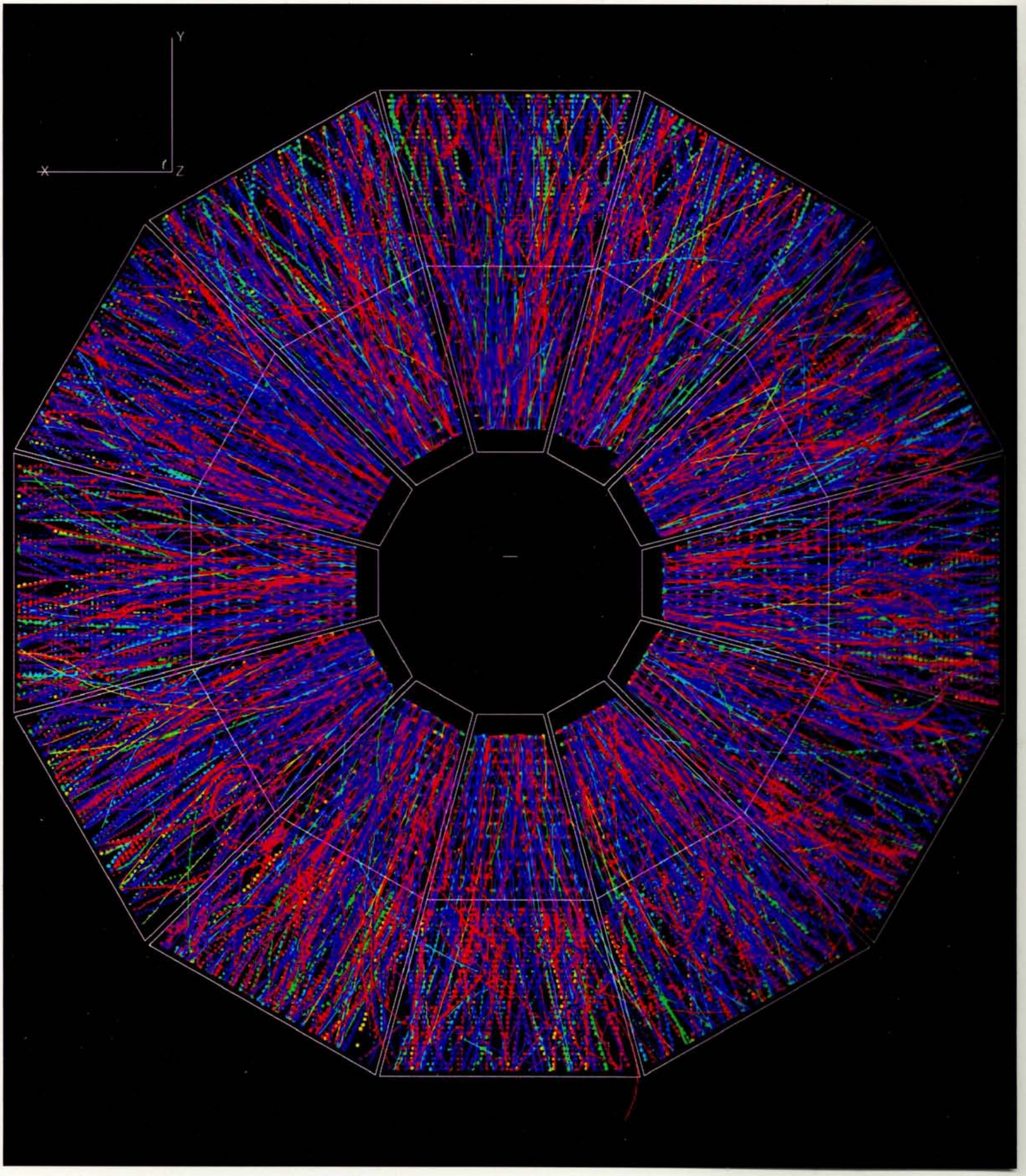


CHIRAL SYMMETRY RESTORATION
(MELTING THE VACUUM)
ON THE LATTICE

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

T
(funny units)

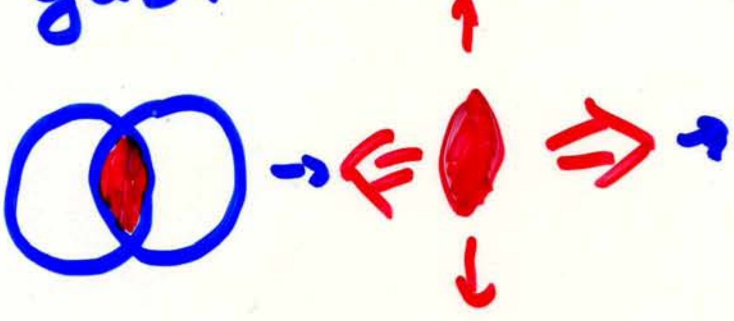
- Everybody always knew that at, say, 1.5 - 2 T_c QCD is not yet weakly coupled.
- Also, even if QCD <u>were</u> weakly coupled, there are strong long distance magnetic interactions
- BUT: the lattice calculations showed that from $2T_c$ to $T \to \infty$ NO THERMODYNAMIC QUANTITY changed by more than ~20%.
- So, people assumed that a quasiparticle picture worked everywhere above T_c, even if the quark and gluon quasiparticles were not yet truly weakly coupled...



STAR

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.)

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

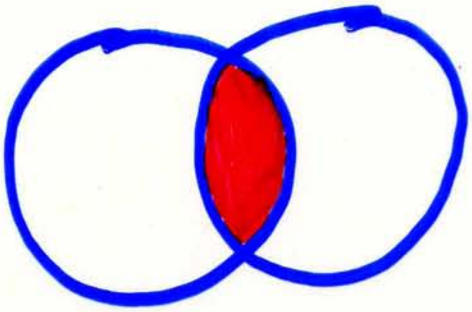
$\Gamma > 0.2$ ruled out

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

$\eta/s \sim 10$ in water

ELLIPTIC FLOW

Indicates extent of early equilibration:



IF: just lots of p-p collisions, followed by free streaming

THEN: final state momenta uniformly distributed in azimuthal angle

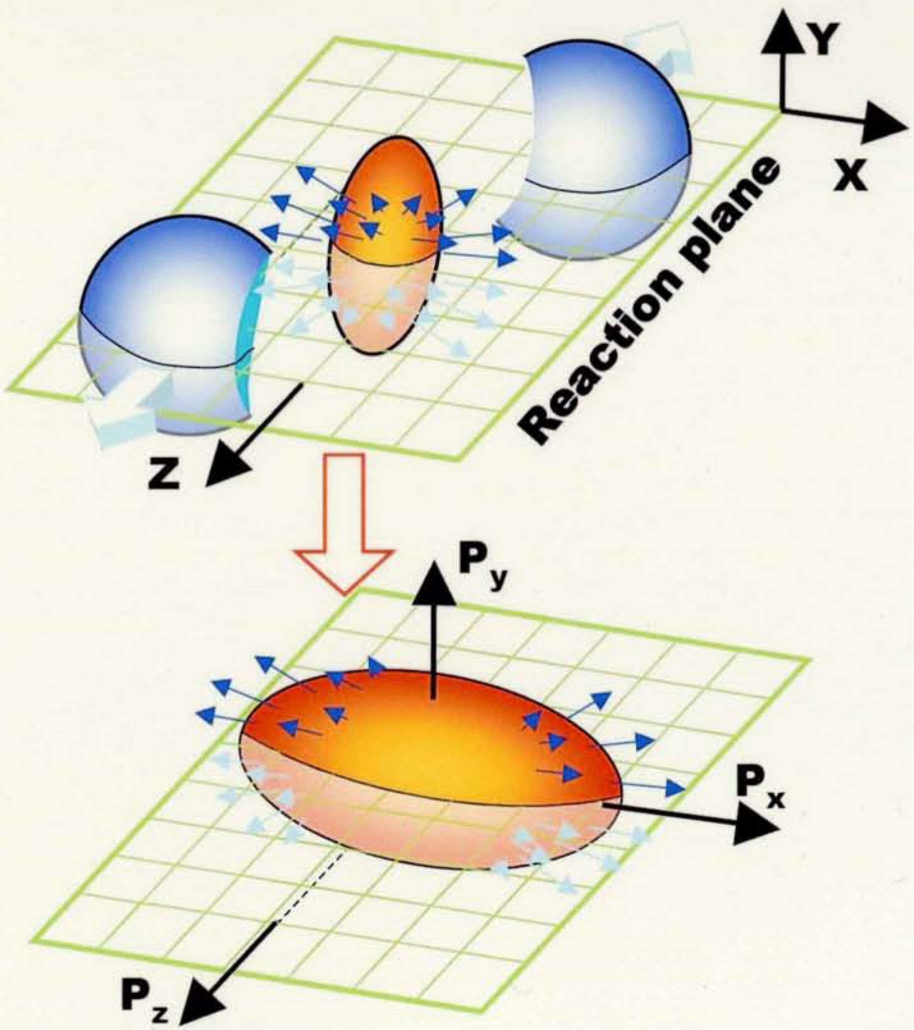
IF: interaction → equilibration → pressure; pressure gradients → collective flow EARLY,

before  circularizes,

THEN: azimuthally asymmetric explosion, final state momenta.

$v_2 \sim \langle \cos 2\phi \rangle \neq 0$

Expansion In Plane



spatial anisotropy ε_2

↓ ↓

momentum anisotropy v_2

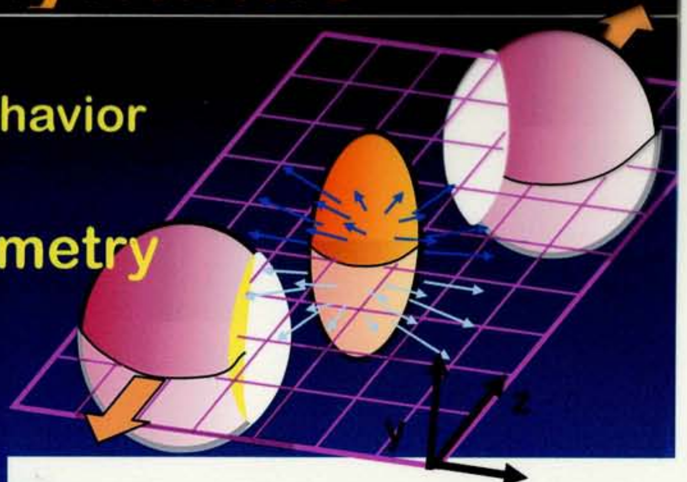
Motion Is Hydrodynamic

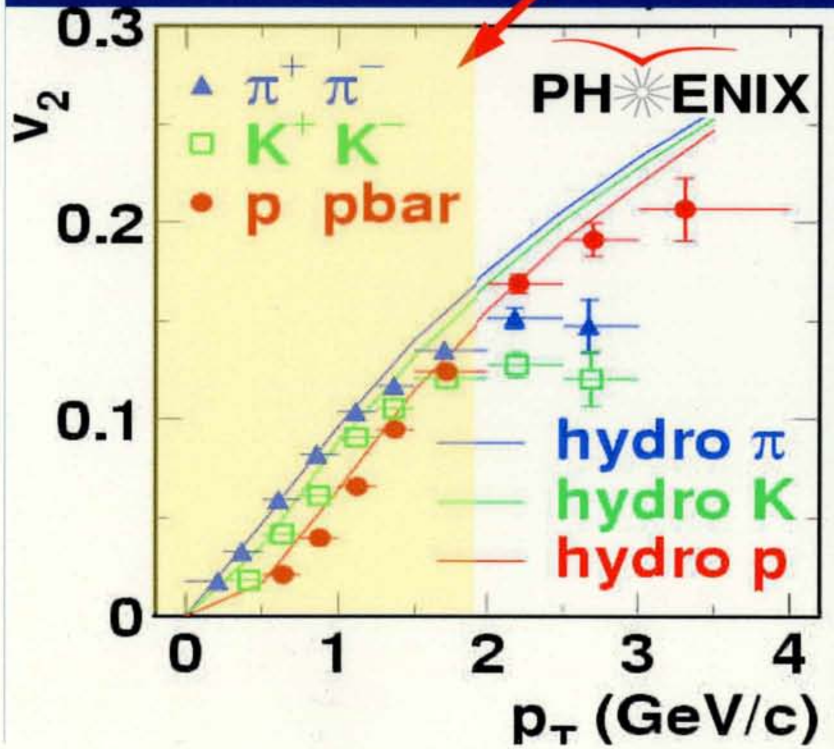
When does thermalization occur?

Strong evidence that final state bulk behavior reflects the initial state geometry

Because the initial azimuthal asymmetry persists in the final state

$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$





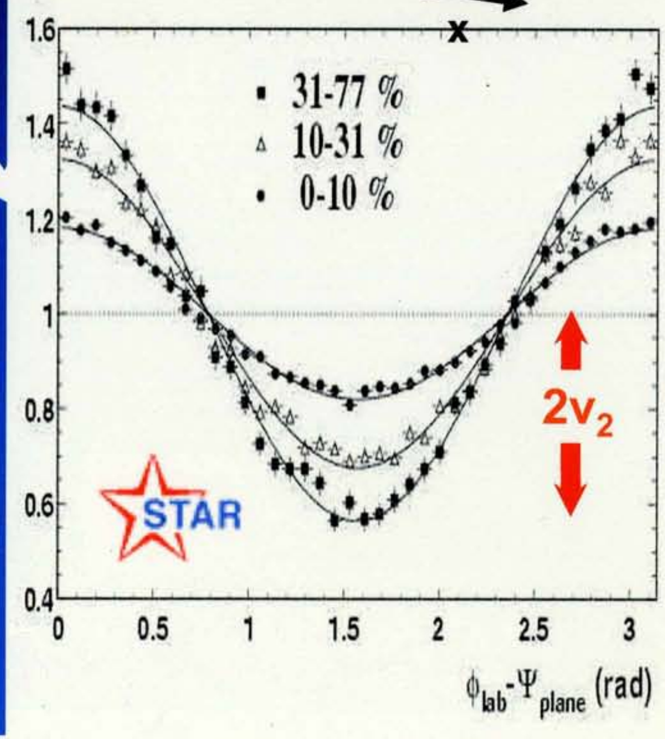


fig: W. Zajc

- Ideal hydrodynamics ASSUMES local equilibrium; zero mean free path; zero dissipation
- Hydro never agreed with v_2 data before RHIC. (At SPS, $v_2^{data} \sim \frac{1}{2} v_2^{hydro}$.)
- At RHIC, hydro does good job of describing v_2, spectra for $p_T < 1$-2 GeV

$\Rightarrow$ "hydro works" by 0.6 - 1 fm after collision

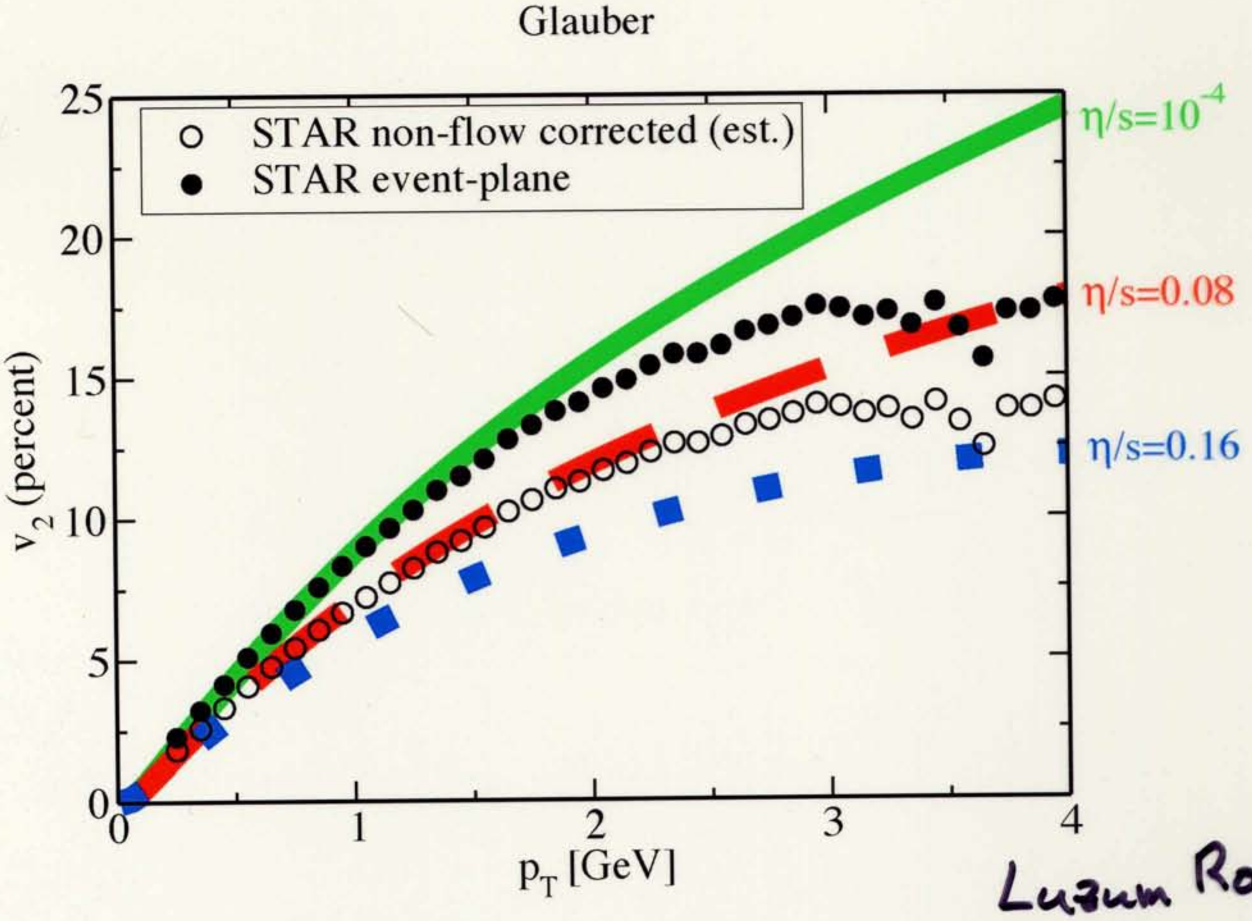
Kolb Heinz

- Challenge to theory: how can equilibration occur so quickly?
- Also, $\Rightarrow$ small shear viscosity

$$\frac{\eta}{s} < 0.2$$ Teaney

- Challenge: precise extraction of η/s, ie bounding it from below, requires hydro calculations $\bar{w}$ $\eta \neq 0$; + precise constraints on initial conditions. Muronga; Heinz Song; Romatschke^2; Dusling Teaney; .....

VISCOUS HYDRODYNAMICS

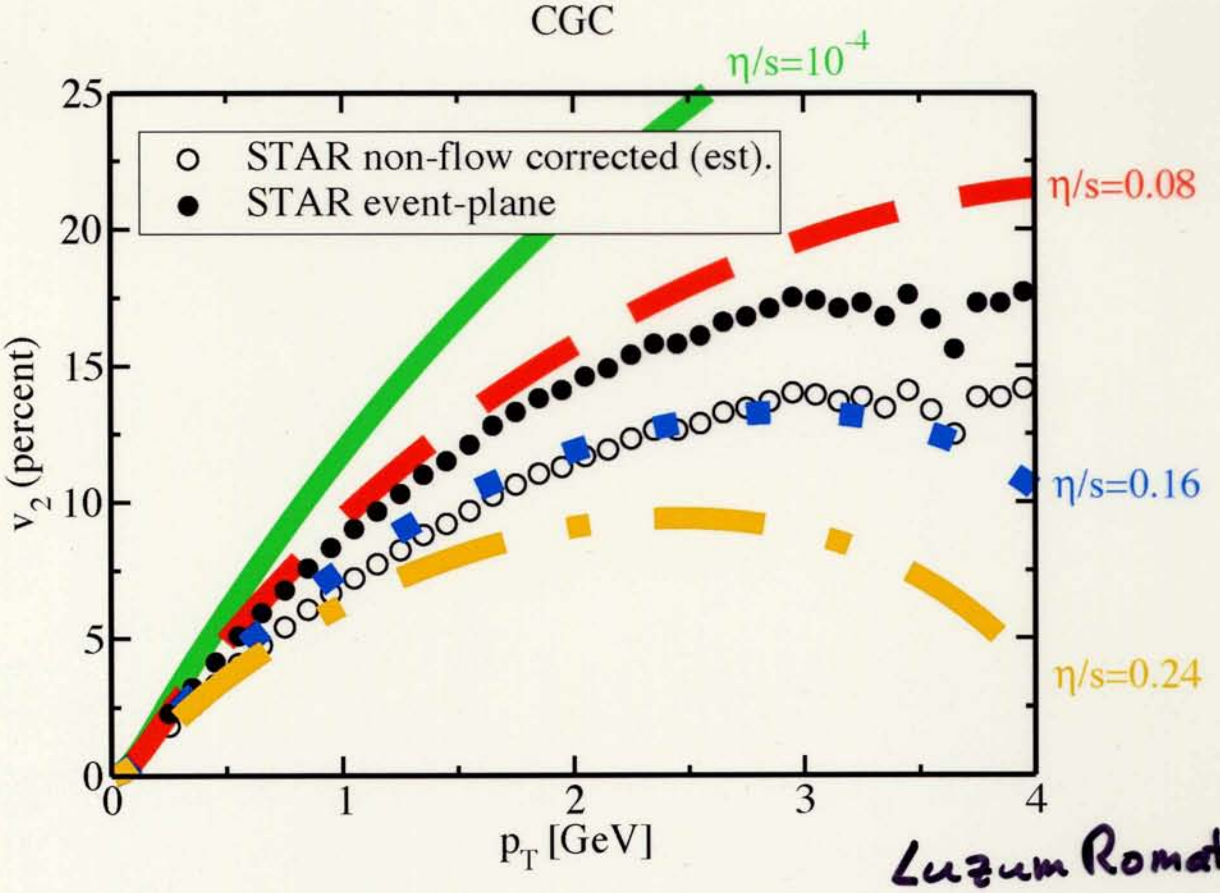


Luzum Romatschke

Data: removing non-flow lowers v_2

Hydro: viscosity lowers v_2

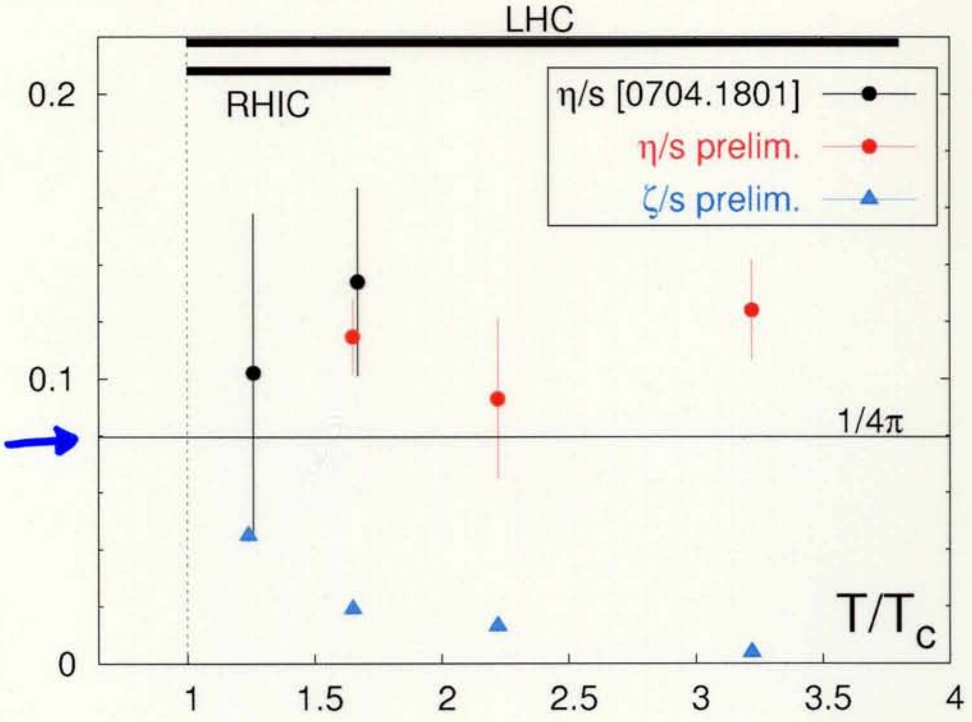
Initial Conditions? →



Luzum Romatschke

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

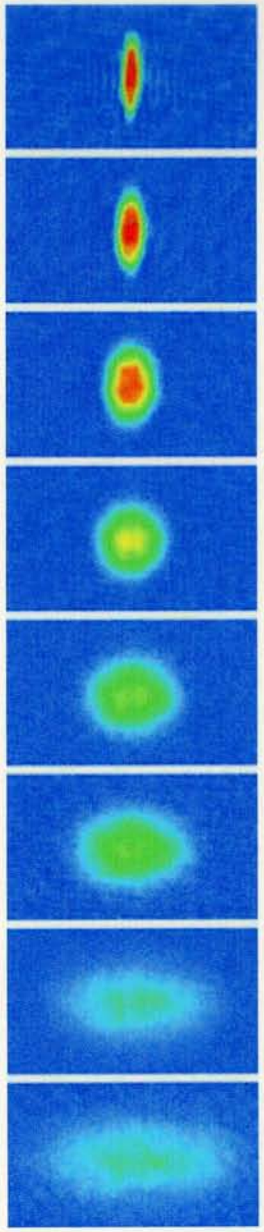
$\frac{1}{4\pi} \rightarrow$

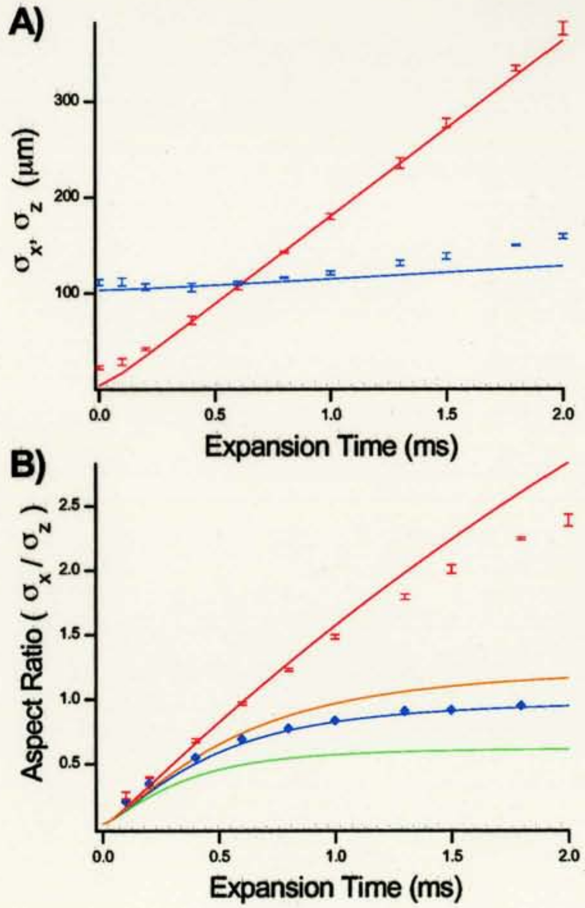


$N_\tau = 8 \quad N_f = 0$ Harvey Meyer '07

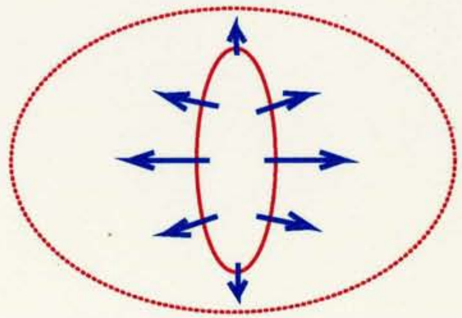
- Conformality $\Rightarrow$ $\zeta/s = 0$
  η/s = T-independent
- And, no sign of T-dependence for η/s over $T_{RHIC} \rightarrow T_{LHC}$.
- Suggests QGP as liquid-like at LHC as at RHIC.

Elliptic Flow of cold fermionic atoms, at unitary point





Hydrodynamic expansion converts coordinate space anisotropy to momentum space anisotropy

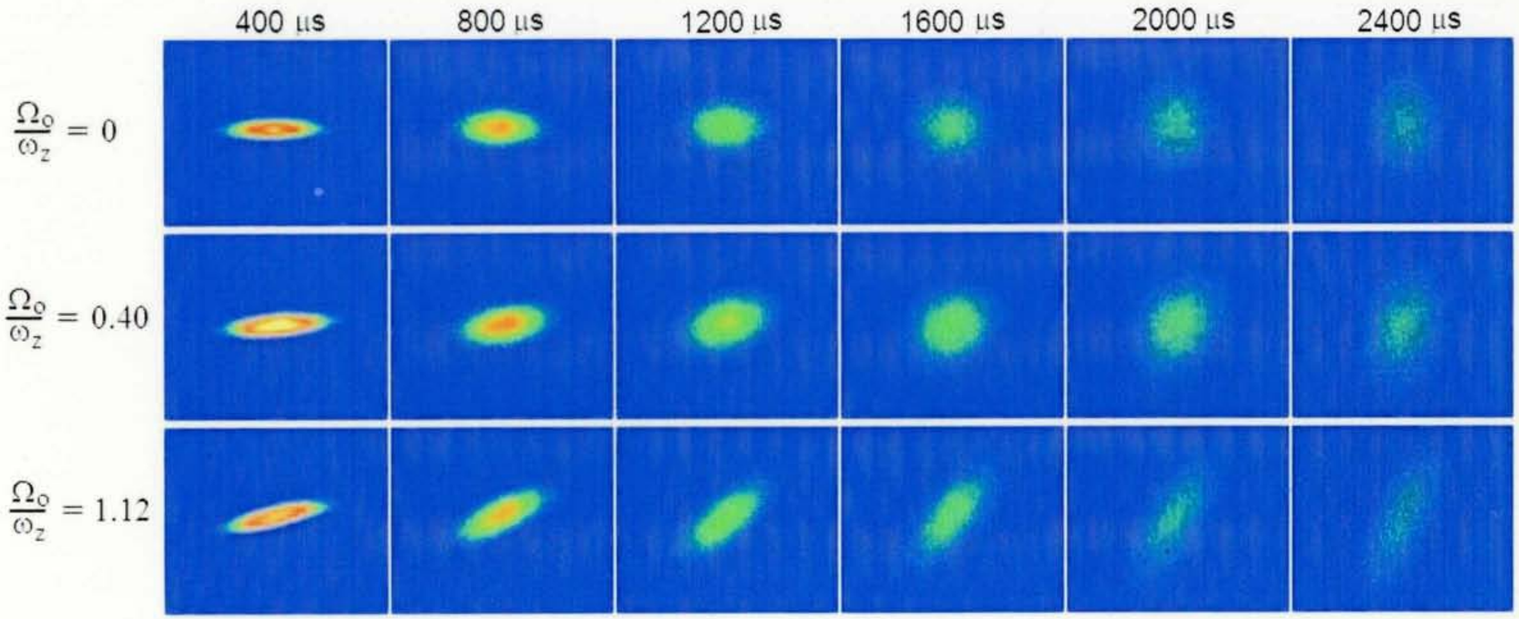


Data: Duke group

Transparency: Schaefer

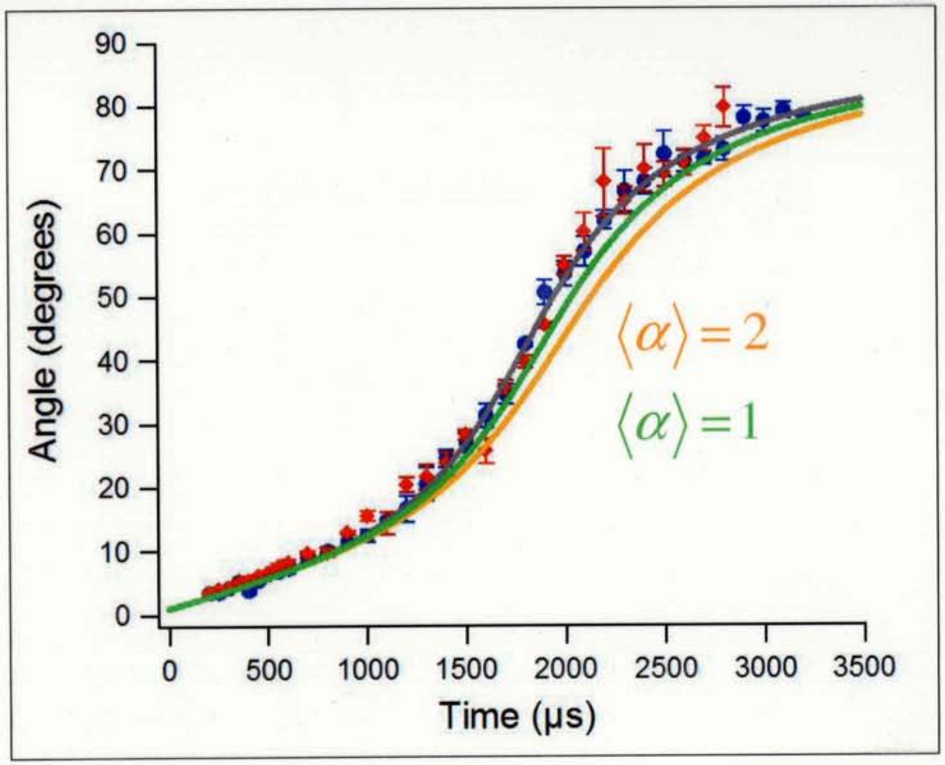
Expansion of a rotating strongly interacting Fermi gas

Duke Physics
Atom Cooling and Trapping



How low is the viscosity?

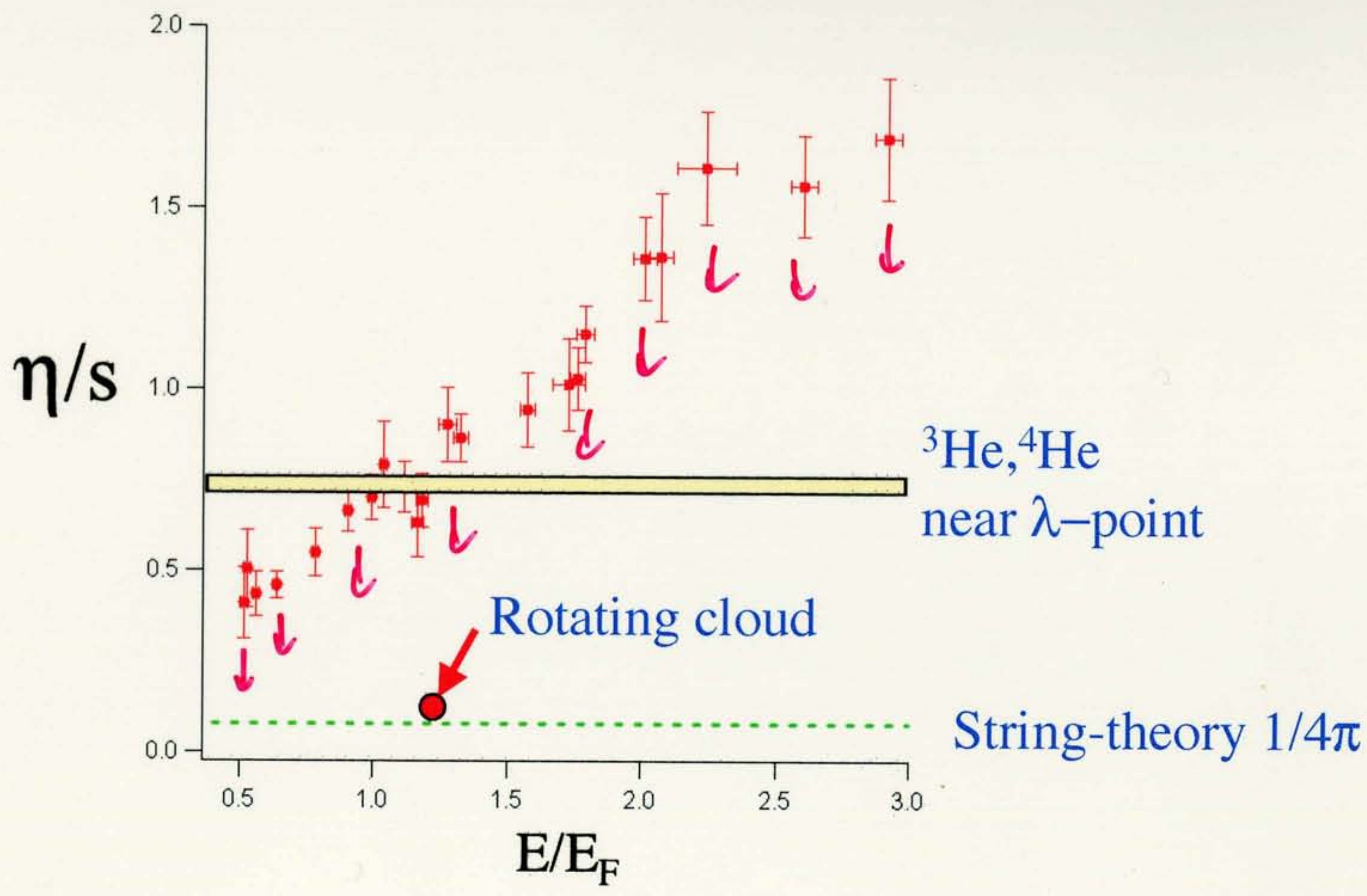
Duke Physics
Atom Cooling and Trapping



- $\Omega_0 = 0.40\ \omega_z$; $E = 0.56\ E_F$
- $\Omega_0 = 0.40\ \omega_z$; $E = 1.21\ E_F$

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. $\therefore$ calculations easy at strong coupling.

THERMODYNAMICS

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

SHEAR VISCOSITY

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

Policastro, Starinets, Son

- For <u>any</u> 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???

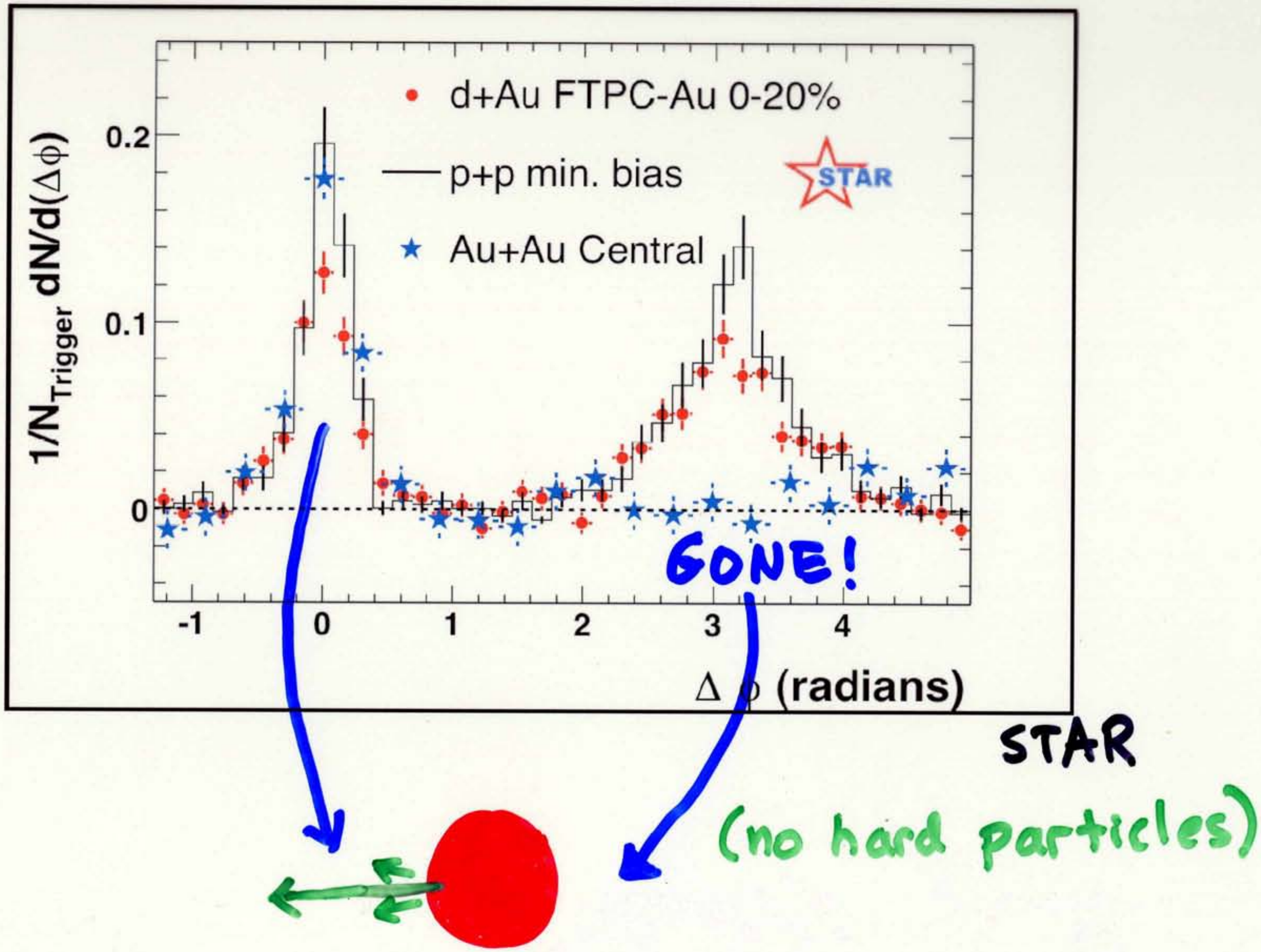
  Son; Balasubramanian Mcgreevy; Adams, B, M]

To what quantities does it apply?

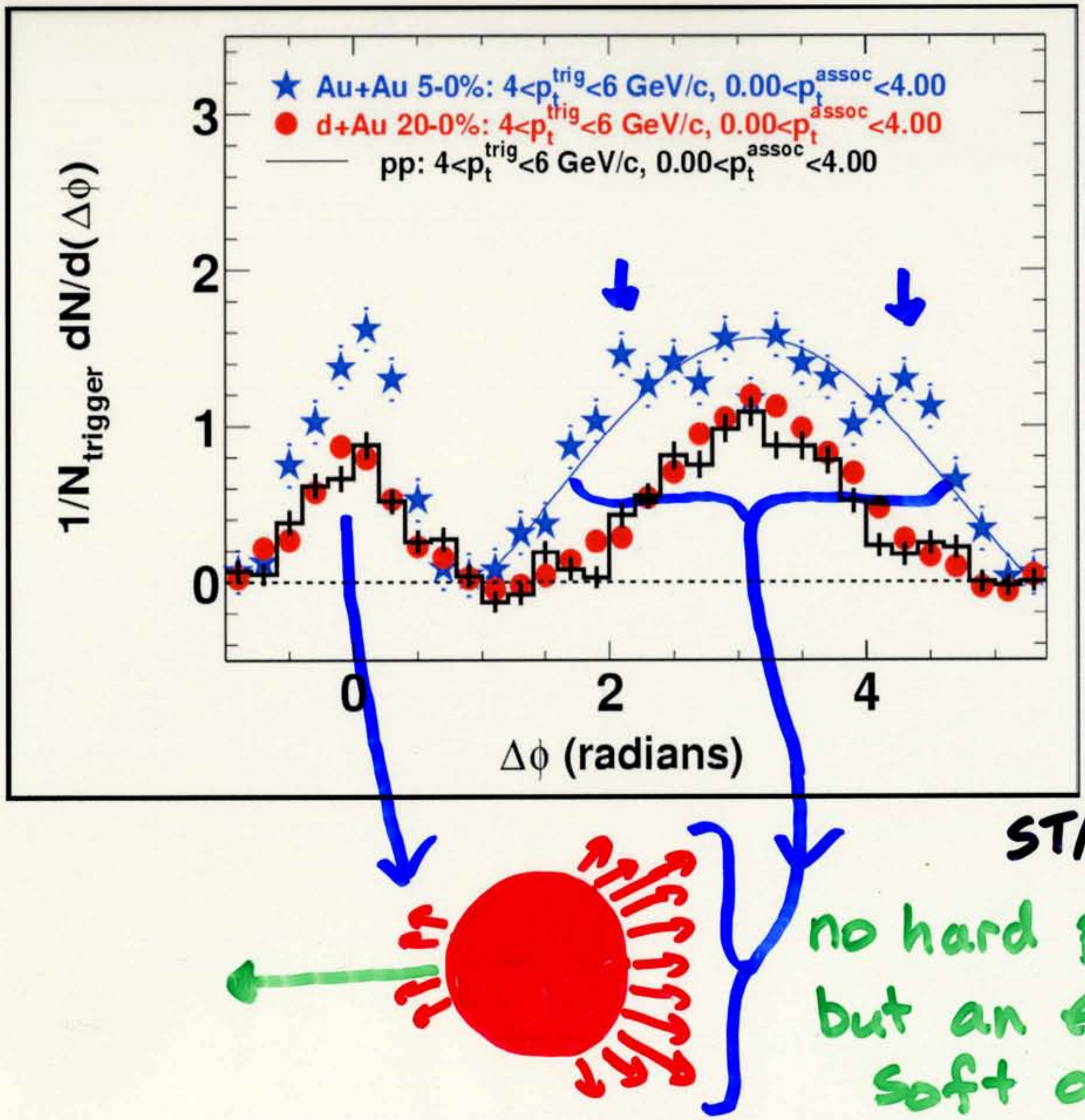
- η/s?
- other suggestions on the QCD side relate to "jet quenching"....

  [Could one study "atom quenching"??]

JET QUENCHING, I



JET QUENCHING II

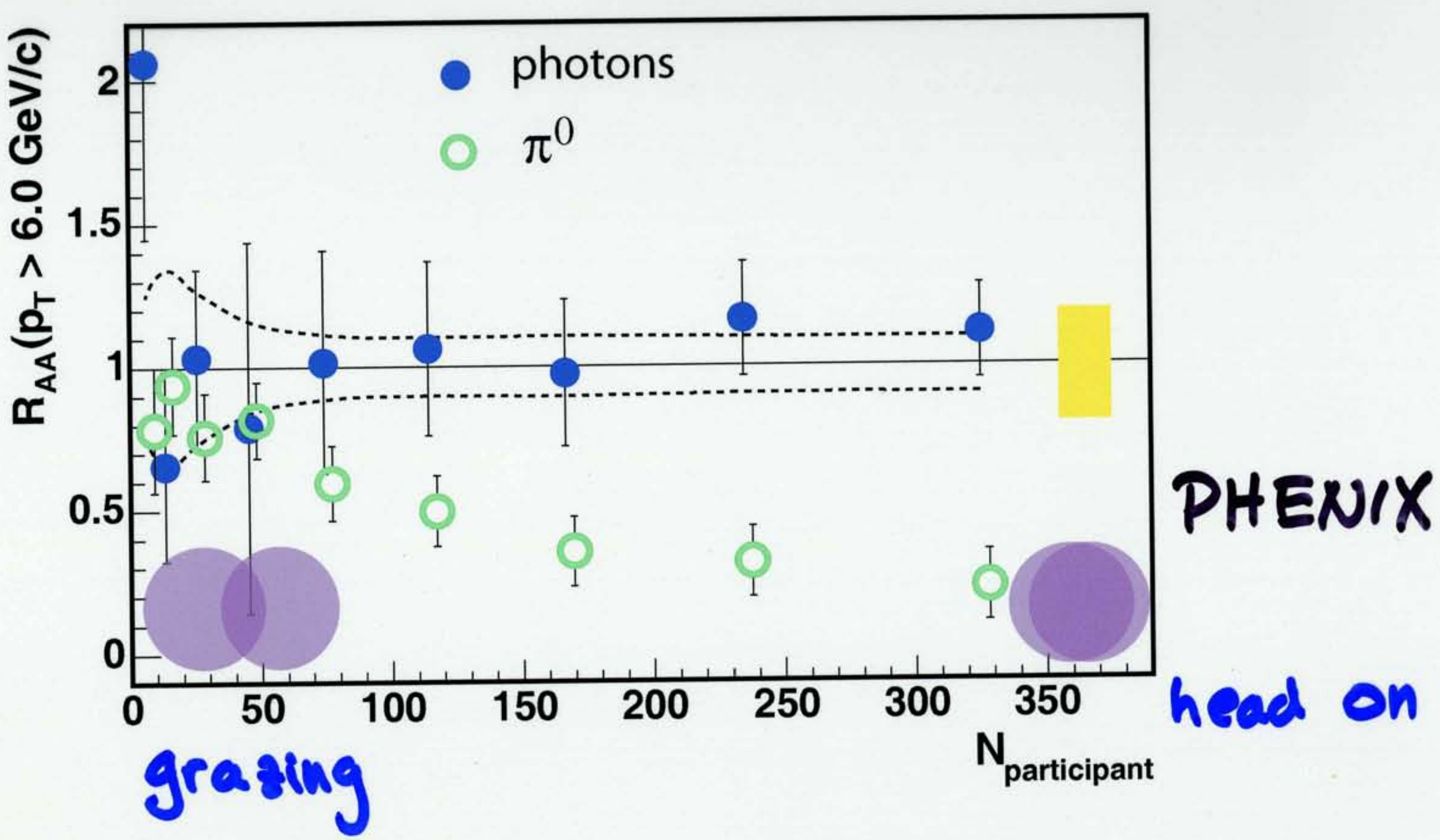


STAR

no hard particles, but an excess of soft ones

JET QUENCHING, III

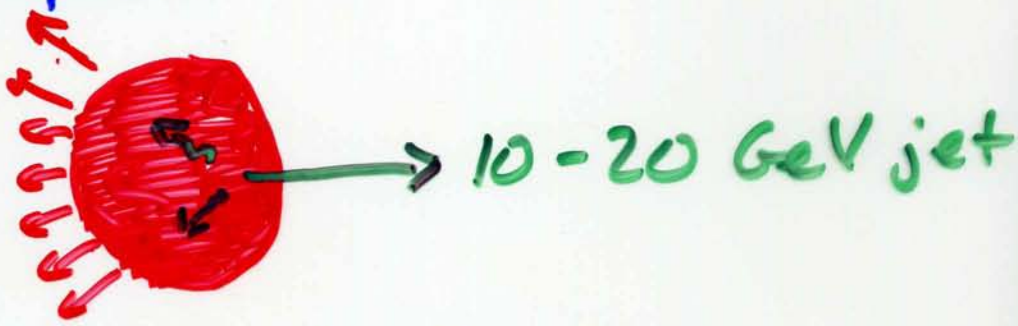
CONTROL EXPERIMENT: 6 GeV pions are missing
6 GeV photons shine through



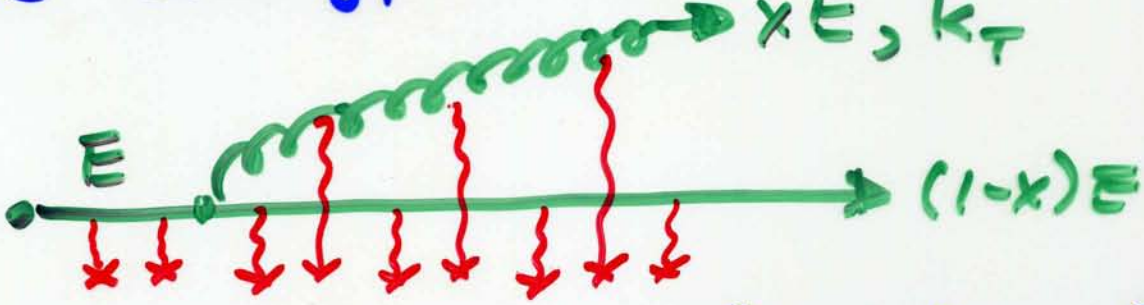
$$R_{AA} = \frac{\text{\# seen in Au-Au collision}}{\text{\# expected if just independent p-p collisions}}$$

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

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

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

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,

  $\hat{q} \sim \frac{\mu^2}{\lambda}$ ← (Debye screening length)$^{-2}$ ← mean free path

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

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

  $\simeq 0.9$ GeV^2/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 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

  ~ 8 GeV^2/fm Hirano, Armesto, Cacciari, Salgado @ QM2008

- 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: $N_c = 3$, $\alpha = 1/2$
  $\rightarrow \hat{q} = 5\ \mathrm{GeV}^2/\mathrm{fm}$ 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 $\left(\hat{q}/\sqrt{\lambda}\,T^3\right)/\sqrt{S/N_c^2 T^3}$ 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
by 10% @ T = 300 MeV

Liu KR Shi

UPON TAKING THESE TWO STEPS:

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 moving through the strongly coupled plasma of $\mathcal{N}=4$ SYM with

$v > v_{sound} = 1/\sqrt{3}$ but $\frac{1}{(1-v^2)^{1/4}} < \frac{M}{\sqrt{\lambda}\, T}$

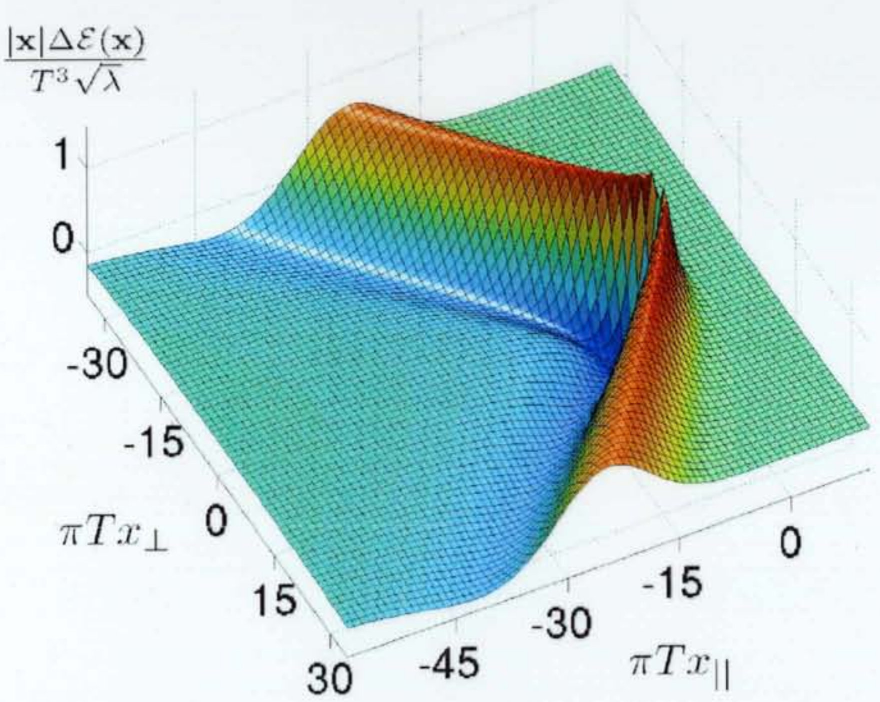
we now know: Friess Gubser Michalogiorgakis Pufu Yarom; Chesler Yaffe; Noronha Torrieri Gyulassy; ...

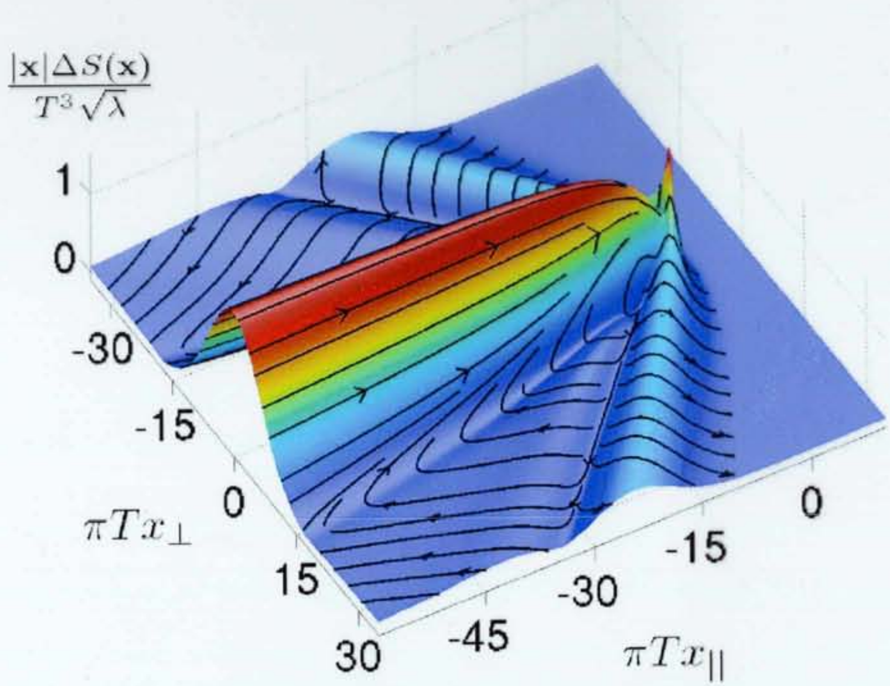
- Mach cone
- and wake

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

- INSIGHT: a point particle <u>does</u> make a Mach cone
- Very similar cone + wake for a point quark, with its color field, moving through QCDQGP, assuming small η.

Neufeld Müller Ruppert



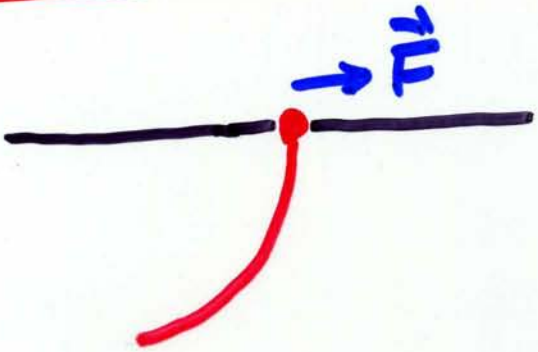


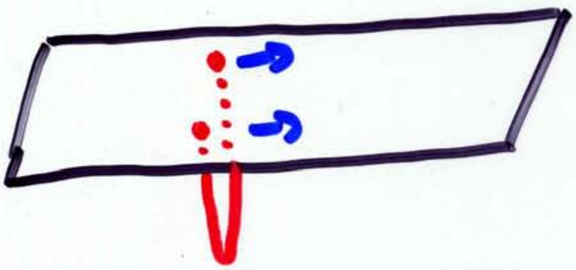
Energy density.
Nb: Specific heat $\propto N_c^2$ amplifies effect of heat over motion in $\mathcal{E}$. So, this plot tells you where there is heating. Ie compression. Ie SOUND.

Momentum flow.
Mach cone and wake.

Chesler + Yaffe

$\sqrt{\gamma} < M/\sqrt{\lambda}T$ vs. $\sqrt{\gamma} > M/\sqrt{\lambda}T$





string worldsheet timelike

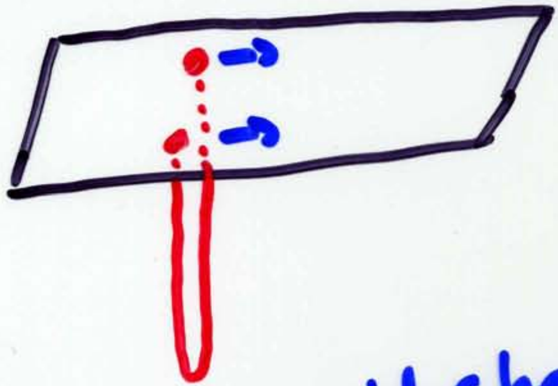
$\langle W \rangle \sim \exp[itE]$

describes screening, with screening length > quark Compton wavelength

No such calculation is possible; $\vec{F}$ needed is so large that pair production copious.

Teaney Casalderrey-Solana

[Also, if $\vec{F}=0$, deceleration due to radiation exceeds that due to drag.]



string world sheet spacelike

$\langle W \rangle \sim \exp[-\text{real}]$

describes DIS or $\hat{q}$.

ROTATING STRING

aka "STIRRING THE PLASMA"

Bitaghsir-Fadafan, Liu, KR, Wiedemann

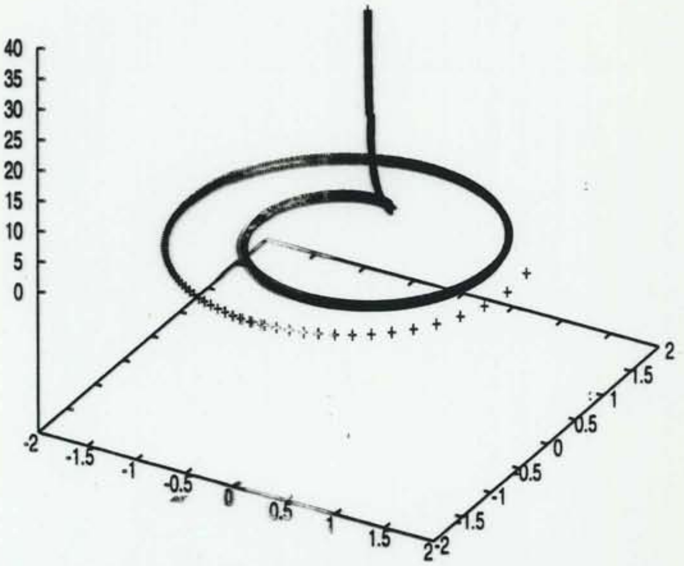


Figure 5: The rotating string drag solution for $\omega = 5.$ and $\Pi_\theta = 100.$. The quark rotates clockwise at the brane ($z \to \infty$) at a radius $\rho(\infty) = 0.1789$. This corresponds to a relativistic quark propagating with 0.895 times the velocity of light. The curve does not end after a finite length, but is plotted her for values of $z \geq 1.005$ only. See text for further details.

a heavy quark moving in a circle with radius ρ, angular frequency ω.

→ provides a clean, but toy, example of crossover from drag to radiation

CALCULATE dE/dt

$\frac{dE}{dt}$ = energy flowing down string

= energy expended by agent moving the quark

= energy dumped into the plasma by stirring it

is calculable à la Herzog et al; Gubser

Compare result to:

i) $$\left.\frac{dE}{dt}\right|_{\text{linear drag}} = \frac{\pi}{2}\sqrt{\lambda}\, T^2 \frac{v^2}{\sqrt{1-v^2}}$$ Herzog et al; Gubser

with $v = \omega \rho$.

ii) $$\left.\frac{dE}{dt}\right|_{\substack{\text{radiation,}\\ \text{in vacuum}}} = \frac{\sqrt{\lambda}}{2\pi} \frac{\omega^2 v^2}{(1-v^2)^2}$$

Mikhailov, cf Liénard

$\frac{\omega}{\pi T}$

$\frac{dE/dt}{\left.\frac{dE}{dt}\right|_{\text{linear drag}}}$

$\frac{dE/dt}{\left.\frac{dE}{dt}\right|_{\text{vacuum radiation}}}$

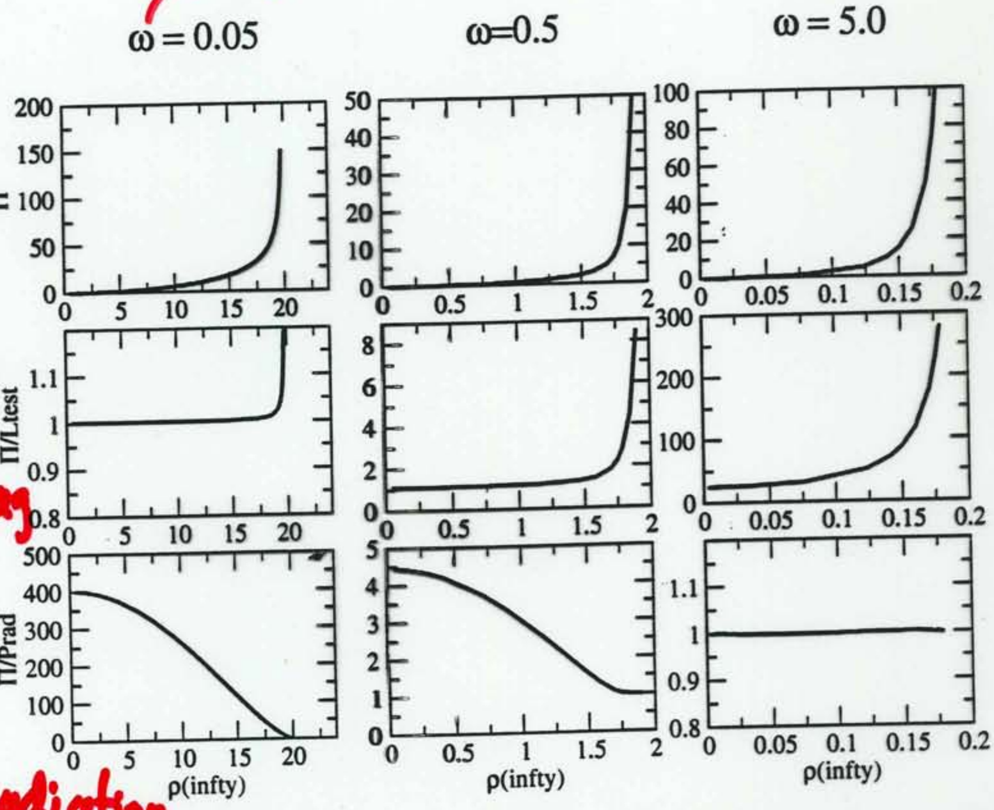


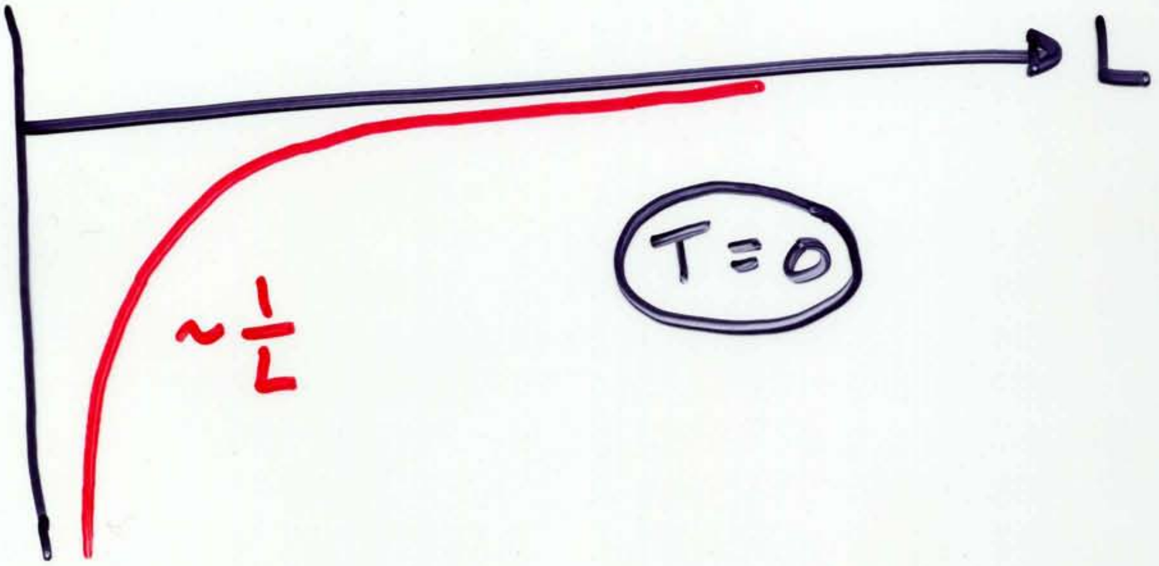
Figure 3: Upper row: Π_θ, which is proportional to the rate of energy loss, plotted as a function of the radius $\rho(z \to \infty)$ on which the quark rotates, for three different values of the angular velocity ω. Middle row: Π_θ, divided by the parametric ansatz (47) for total angular momentum. The figure indicates that for sufficiently low ω and v, but not for large ω or large v, the rate of angular momentum loss and energy loss is proportional to the angular momentum and energy, respectively. Lower row: Π_θ, divided by the parametric ansatz (48) for vacuum radiation of a circularly accelerated charged point particle. The figure indicates that for large ω, this vacuum radiation dominates energy loss.

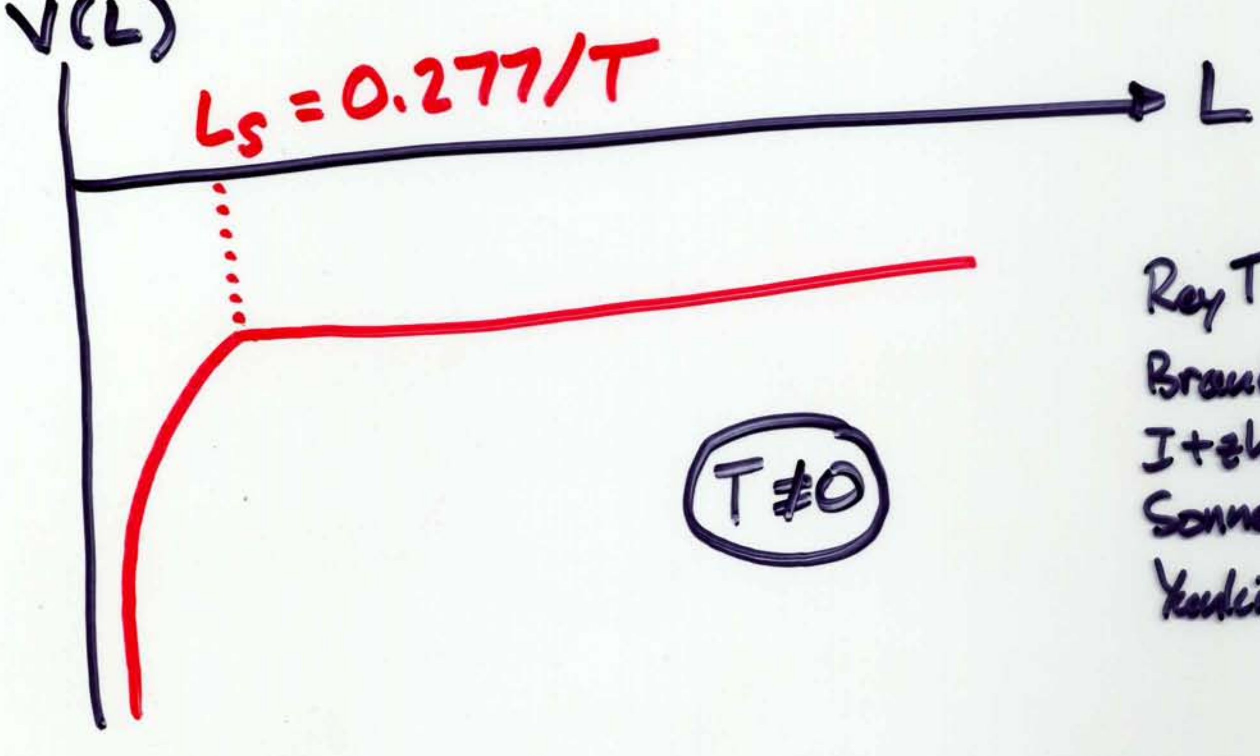
Note: $$\frac{(dE/dt)_{\text{lin. drag}}}{(dE/dt)_{\text{vac. rad.}}} = \frac{(1-v^2)^{3/2}}{(\omega/\pi T)^2}$$

So: result is that wherever one dominates over other, dE/dt well described by the larger.

SCREENING IN N=4

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

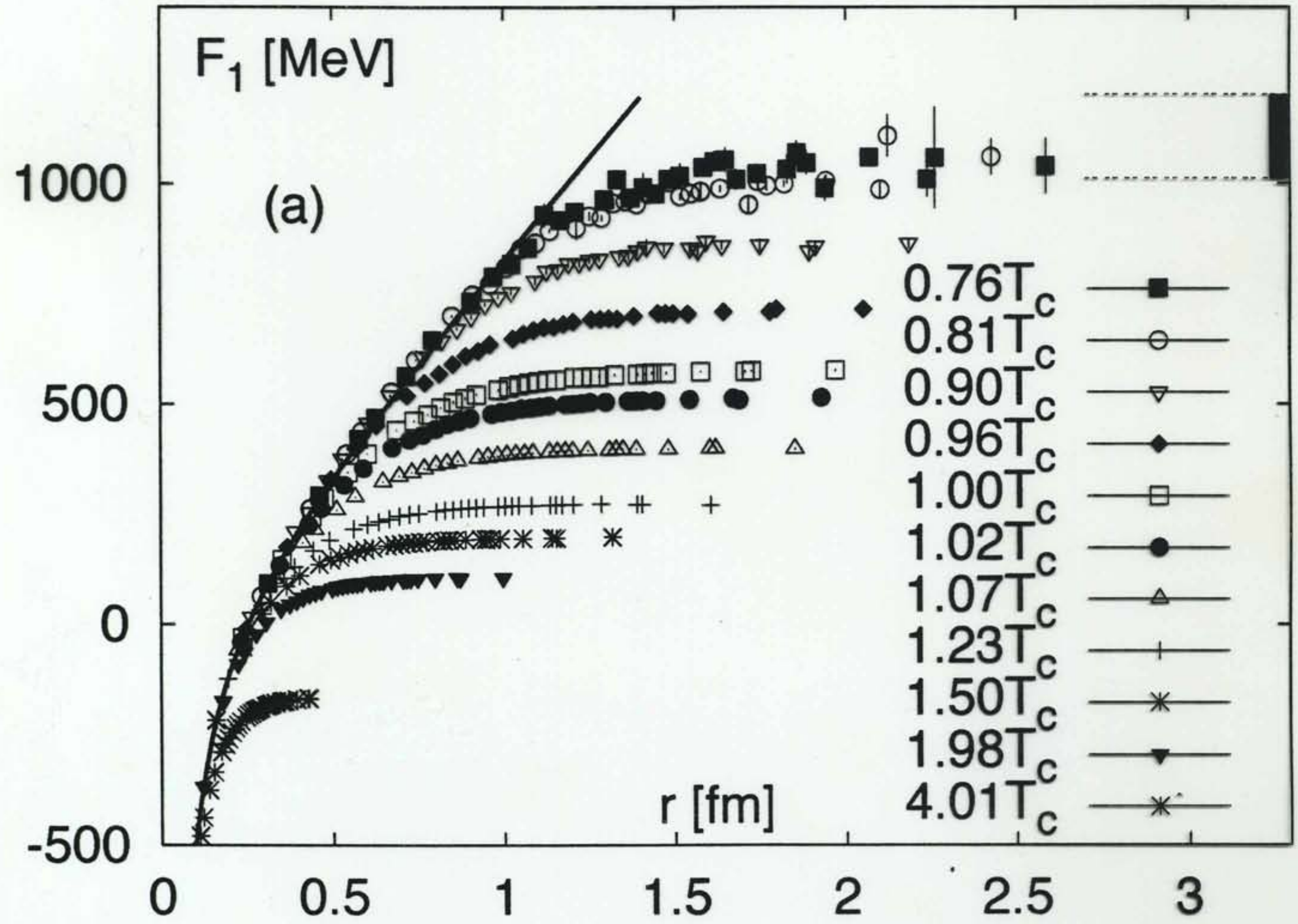




Rey Theisen Yee;
Brandhuber
Itzhaki
Sonnenschein
Yankielowicz

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

SCREENING IN QCD



Kaczmarek, Zantow

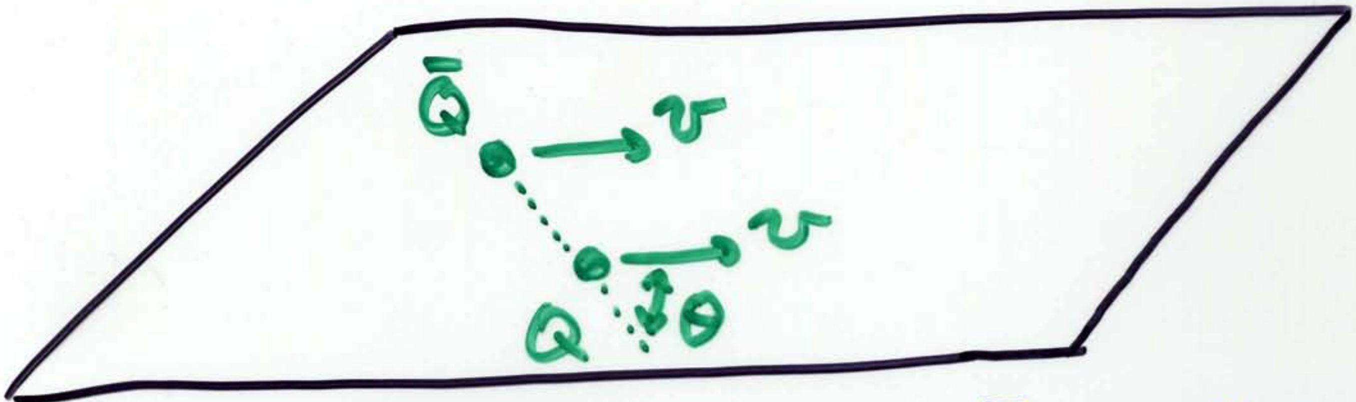
lattice QCD calculation

[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 $Q + \bar{Q}$ <u>moving</u> through the $N=4$ QGP. (Not known how to do this calculation in QCD.) Find:

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

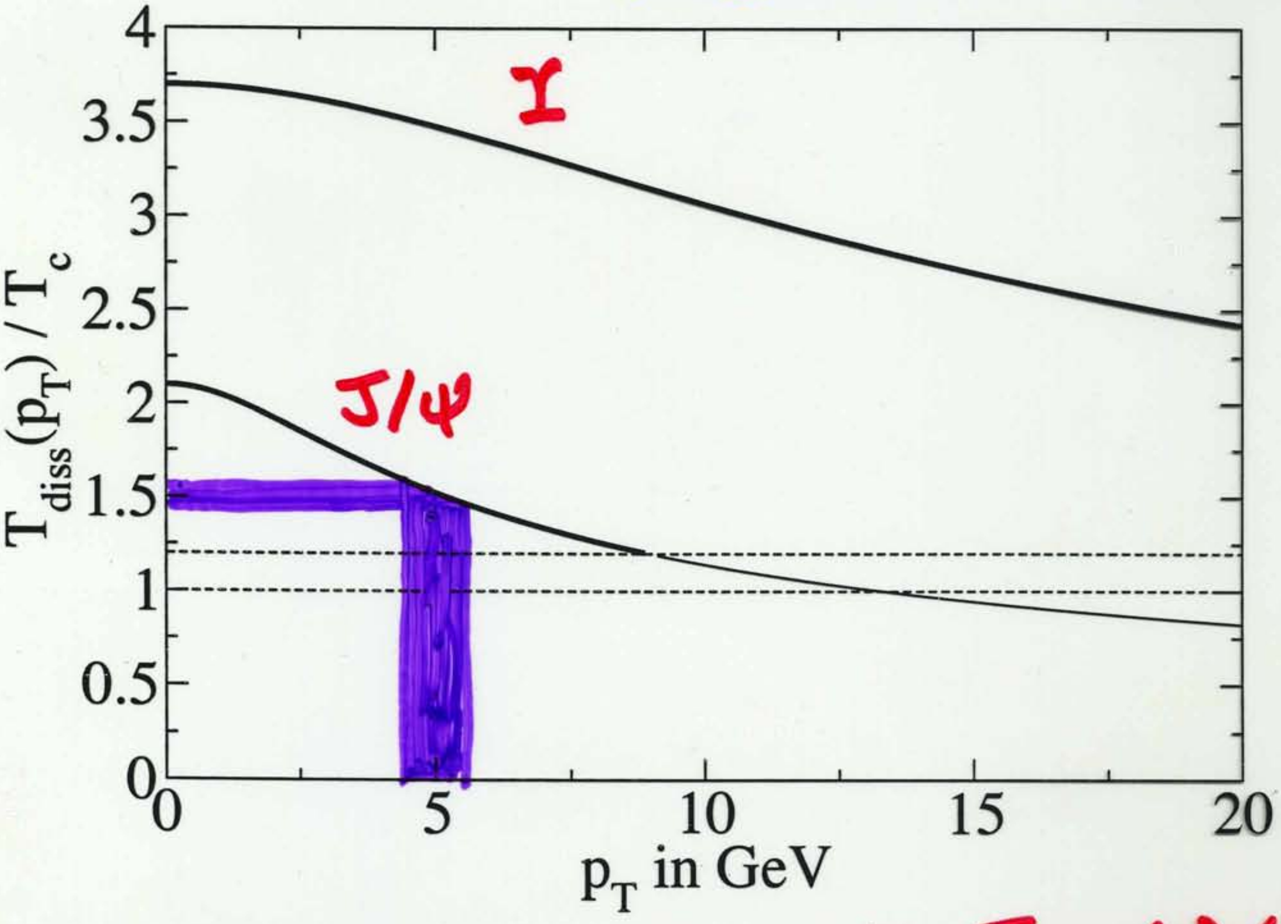
LRW; Peeters et al; Chernicoff et al; Caceres et al

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 <u>themselves</u> dissociate for
$P_T > 5$ GeV if $T_{RHIC} \sim 1.5\,T_c$
$P_T > 9$ GeV if $T_{RHIC} \sim 1.2\,T_c$

"Embedding" the velocity-dependent reduction in T_{diss} for J/ψ's moving through the plasma into a hydrodynamic calculation shows:

- significant drop in J/ψ yield as $P_T \uparrow$
- P_T at which effect sets in is:
  - sensitive to, and $\therefore$ a measure of, $T_{diss}(v=0) - T_{reached}$. [Increasing $T_{diss}(0)$ from 2 to 2.2 GeV pushes this P_T up by ~ factor of 2.]
  - higher for Cu-Cu than for Au-Au

- $R_{AA}^{J/\psi}(P_T)$ at RHIC will be interesting to watch as error bars come down
- Υ'/Υ vs P_T (at LHC) or $\psi'/J/\psi$ even better, since any P_T-dependence of $b+\bar{b}$ or $c+\bar{c}$ production [eg Cronin; eg regeneration; eg gluon energy loss] CANCELS

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

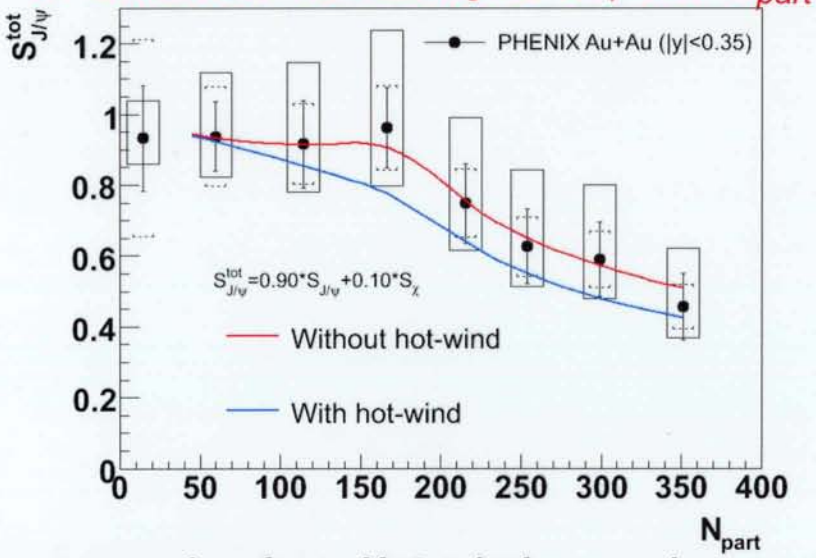
Melting temperature in hot-wind

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

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

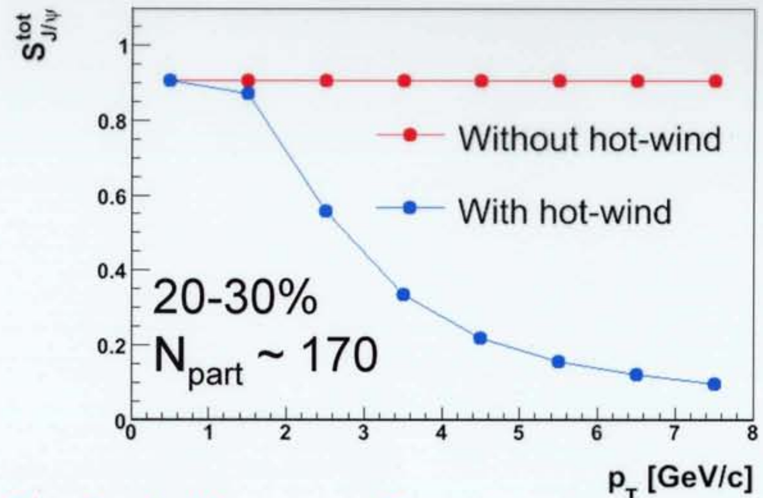
Melting temperatures : $(T_{J/\psi}, T_\chi) = (2.0T_c, 1.34T_c)$
10% feed-down correction

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

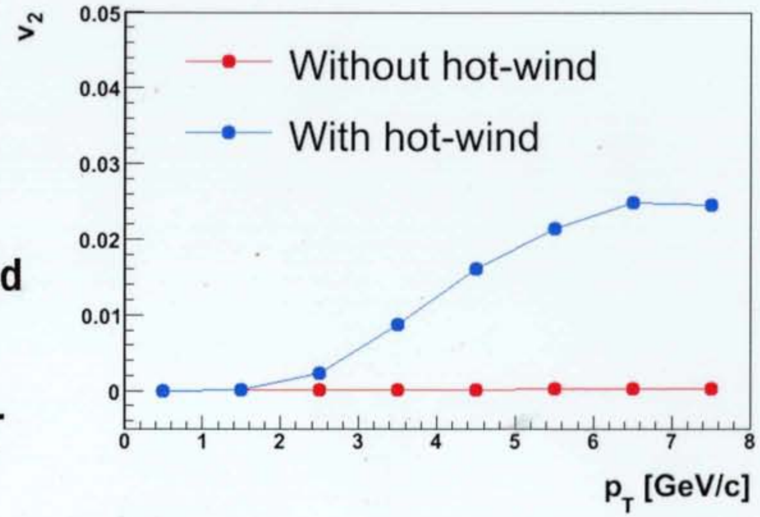


- J/ψ suppression from Hot-wind scenario was calculated in hydro+J/ψ model.
- Overall suppression pattern is similar in both cases.
- Larger suppression and large v2 (~3%) in the high pT region in a scenario with hot-wind.

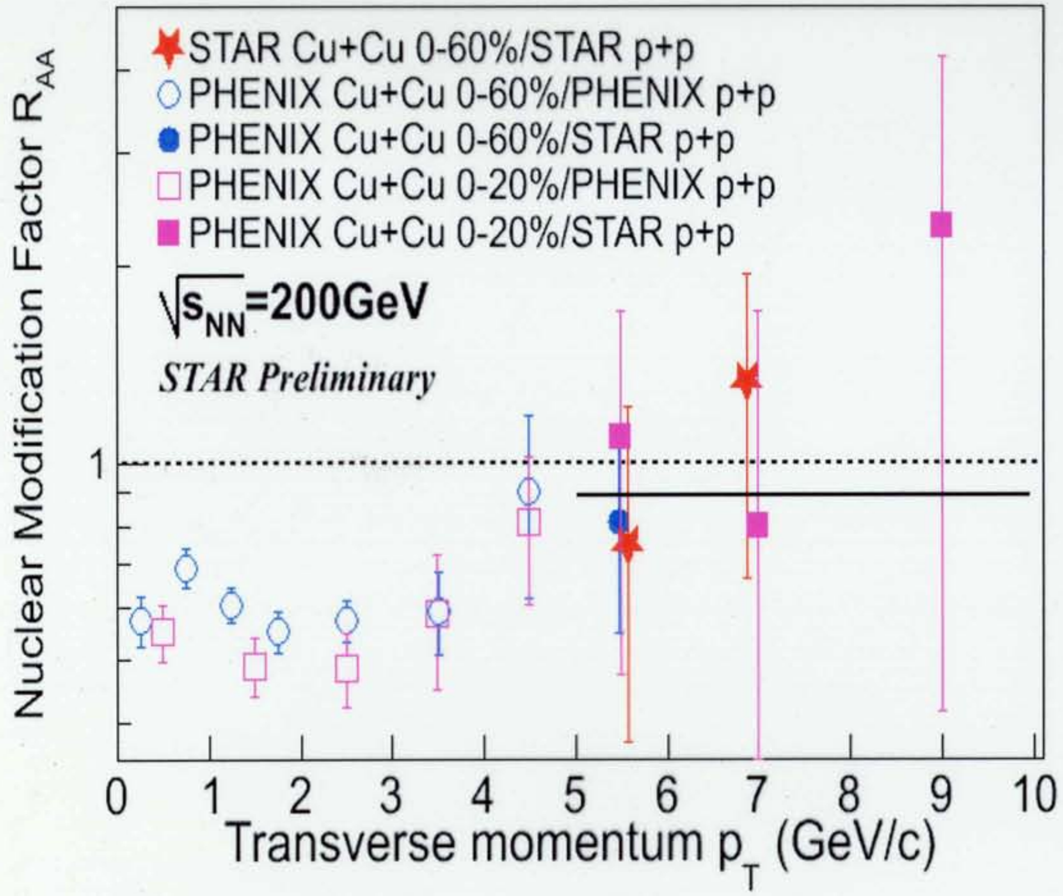
2: Survival Probability of J/ψ vs. pT



3: v2 of J/ψ vs. pT

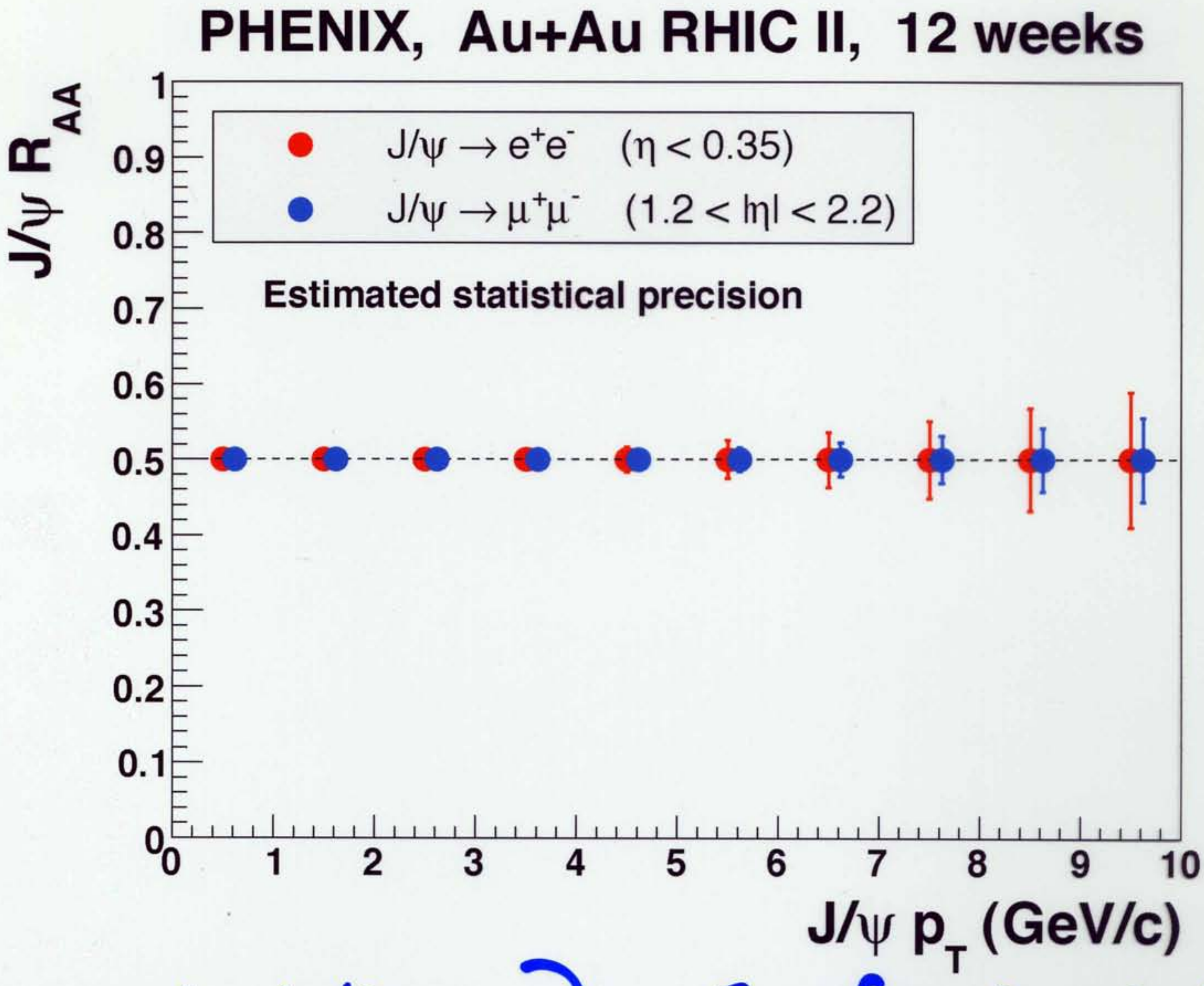


Nuclear modification factor R_{AA}



- Double the p_T range to 10GeV/c
- Consistent with no suppression at high p_T:
  $R_{AA}(p_T>5\ \text{GeV/c}) = 0.89\pm0.20$
- 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

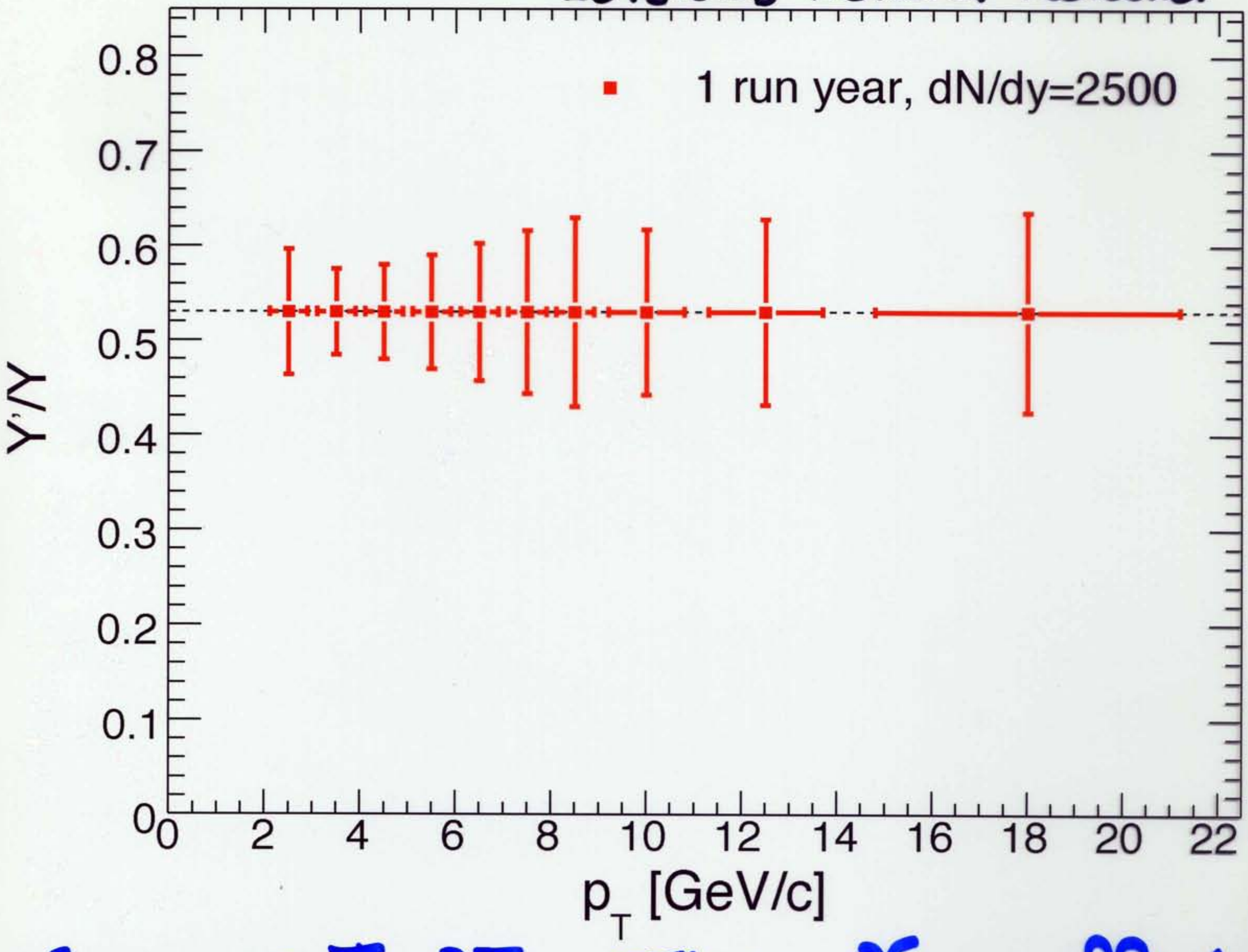
RHIC DATA TO COME



Our calculation + Karsch Kharzeev Satz interpretation of current data $\Rightarrow$ Significant reduction (by ~ factor of 2) of J/ψ yield as p_T increased from 5 to 9 GeV.

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.

LIMITING VELOCITY FOR MESONS

Upon adding heavy quarks to $\mathcal{N}=4$ SYM, mesons ("quarkonia") Karch Katz; Babington et al; Kruczenski et al; Mateos 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

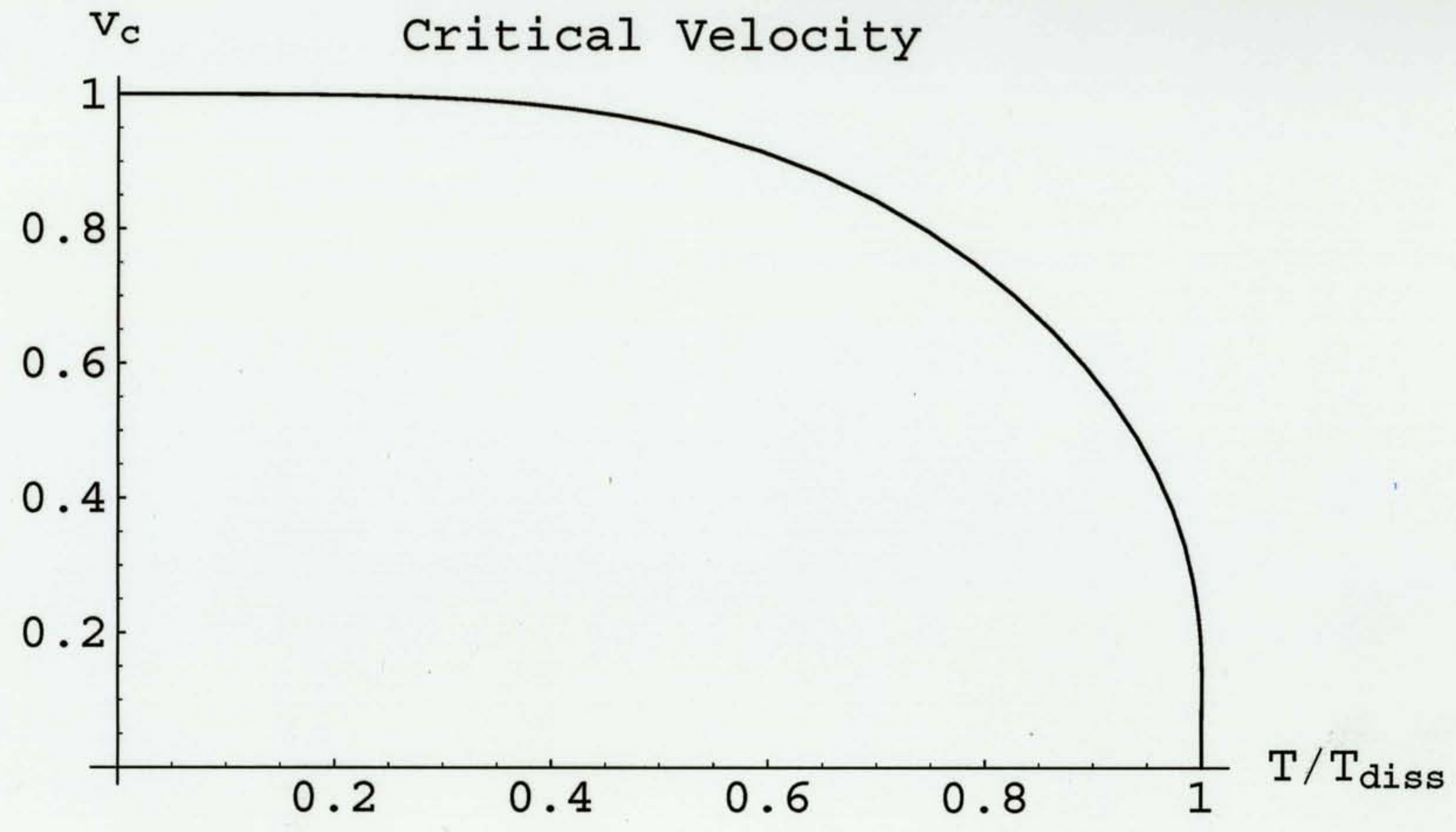
BARYON SCREENING

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.

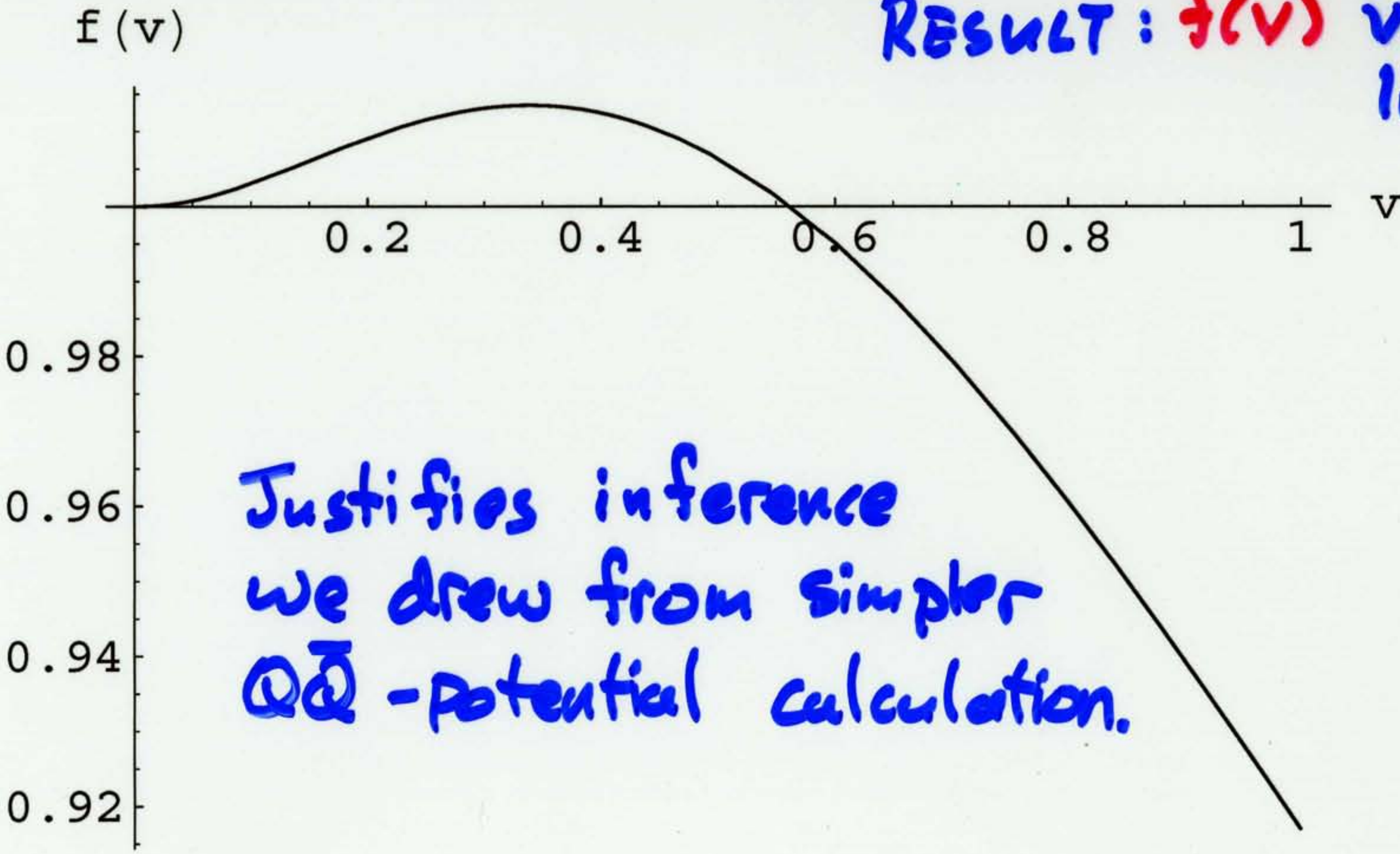
MESON SPEED LIMIT



Ejaz Faulkner Liu KR Wiedemann

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

RESULT: $f(v)$ varies little.

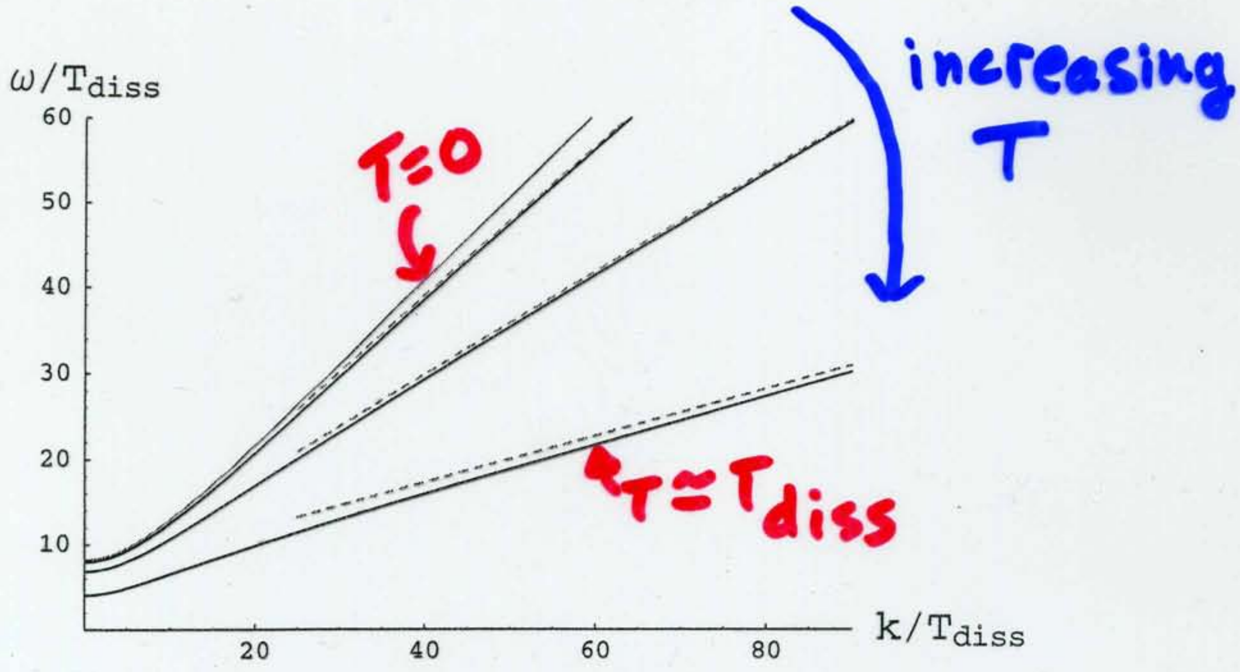


Justifies inference we drew from simpler $Q\bar{Q}$-potential calculation.

Ejaz Faulkner Liu KR Wiedemann

MESON DISPERSION RELATIONS

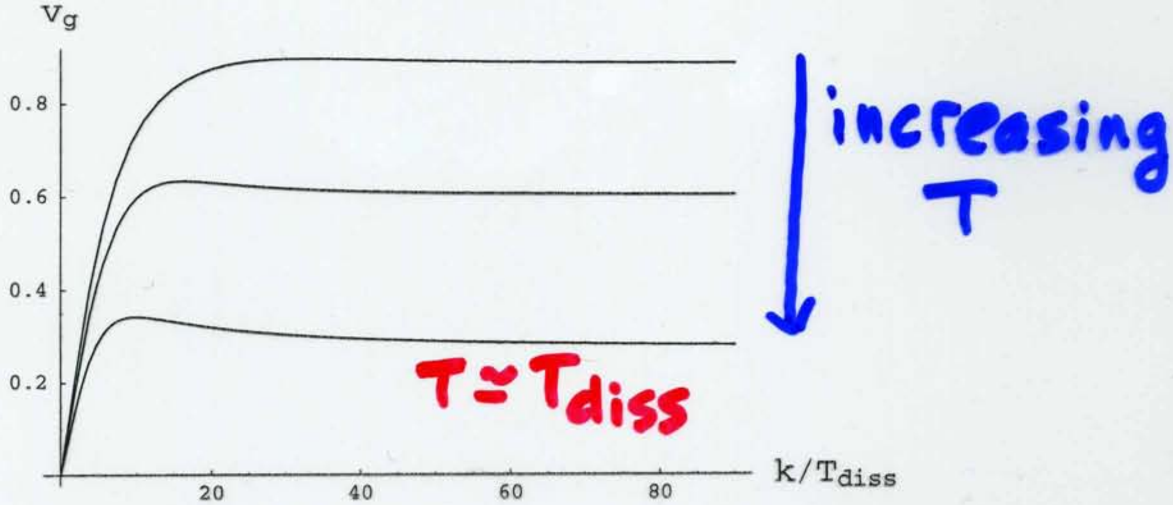
Ejaz Faulkner Liu KR Wiedemann



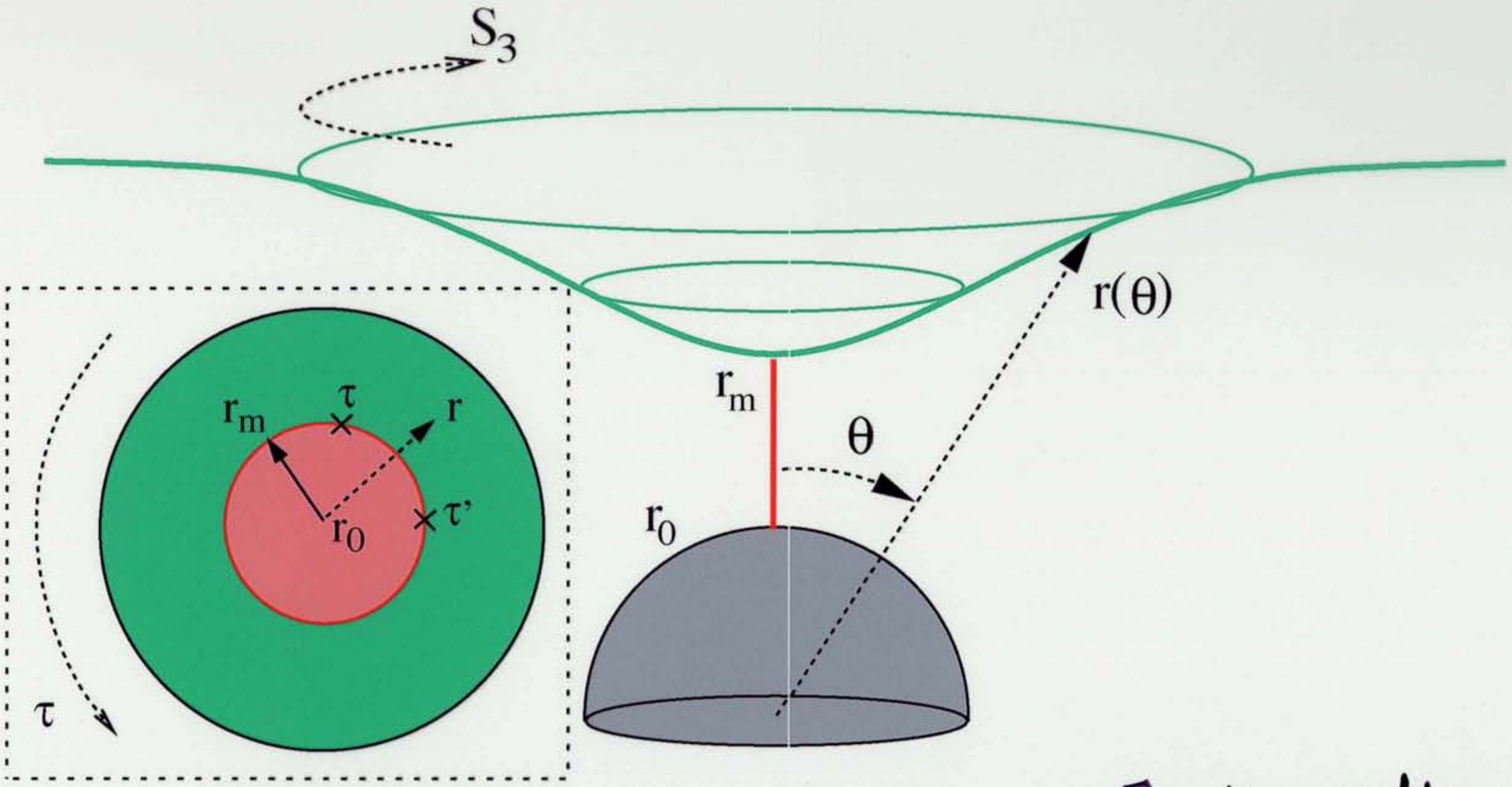
dashed lines: analytic large k result

MESON GROUP VELOCITY

Ejaz Faulkner Lin KR Wiedemann



- limiting velocity
- in this calculation, with $\lambda \to \infty$, meson widths are zero and there is no limit on k, in principle. Velocity dependence of Q-$\bar{Q}$ screening puts a limit on the k of mesons that can actually be produced.

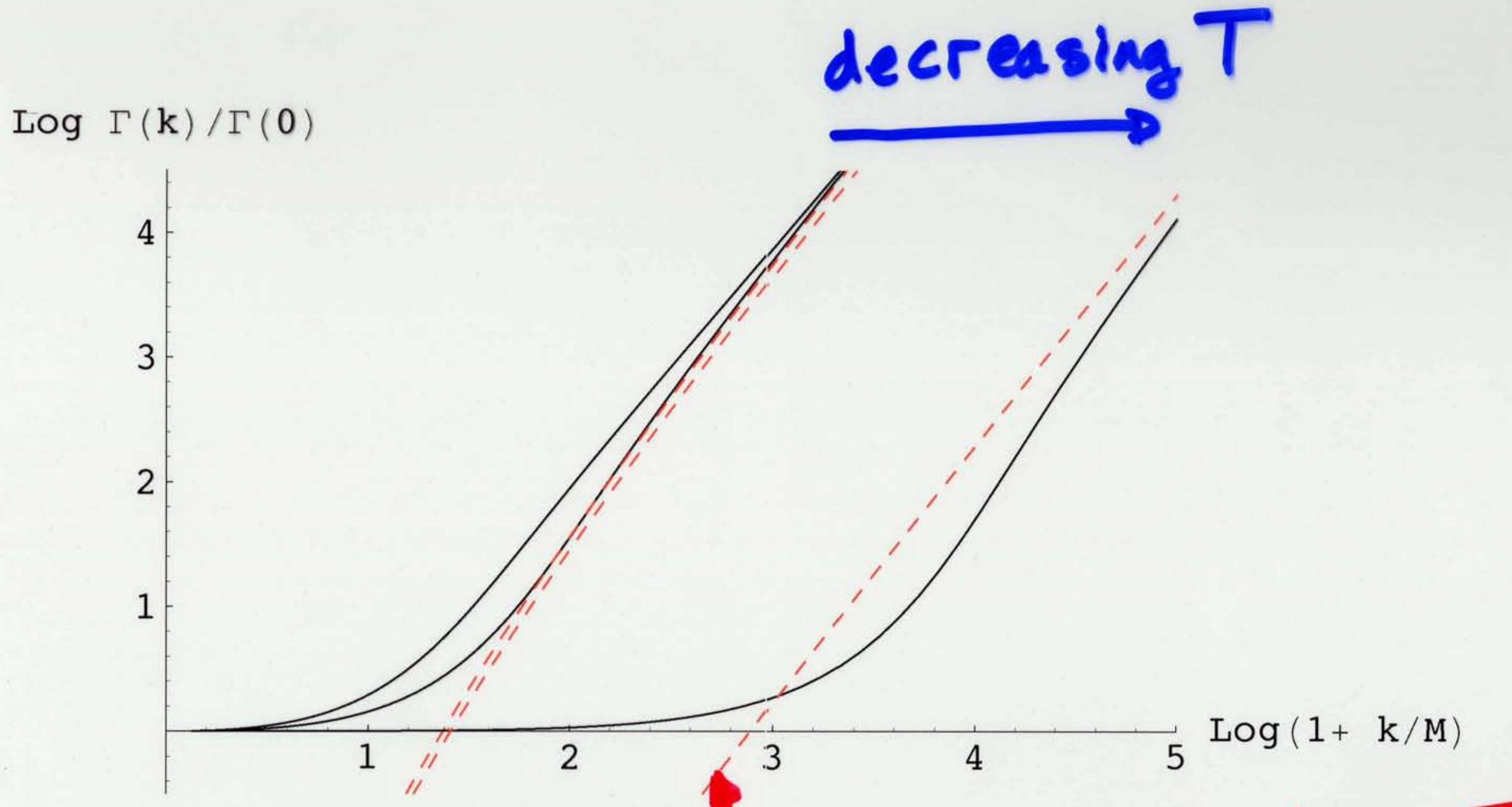


Faulkner Liu

Calculation of width of meson due to

Meson + heavy quark $\longrightarrow$ heavy quark + ...
from plasma

Γ, and n_Q, $\propto e^{-\beta m_Q}$. Calculate $\frac{\Gamma(k)}{\Gamma(0)}$



large-k result, which at low T

becomes: $\dfrac{\Gamma(k)}{\Gamma(0)} = \dfrac{1}{192\pi^2} \dfrac{T^4\lambda^3 k^2}{M_Q^6}$

Using $T_{diss} = \dfrac{2\pi}{2.901} \dfrac{M_Q}{\sqrt{\lambda}} = \dfrac{M_{meson}}{8.205}$

the large-k, low-T result can be recast as:

$$\frac{\Gamma(k)}{\Gamma(0)} = C \quad \text{when} \quad \frac{k}{T_{diss}} = 4.3\sqrt{C}\, \frac{T_{diss}^2}{T^2}$$

or:

$$\frac{\Gamma(k)}{\Gamma(0)} = C \quad \text{when} \quad \frac{T}{T_{diss}} = 1.4\, C^{1/4} \underbrace{\sqrt{\frac{M_{meson}}{k}}}_{= \frac{1}{\sqrt{8}}\ !}$$

[$C \simeq 9$ corresponds to the k at which v_g has its maximum.]

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, $\frac{\hat{q}}{\sqrt{\nu / N_c^2}}$.)

  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:

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

  cf: $= \frac{3}{4} + 1.69\,\lambda^{-3/2}$ ($\mathcal{N}=4$ 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: $= \frac{1}{4\pi}\left(1 + 20.3\,\lambda^{-3/2}\right)$ ($\mathcal{N}=4$ SYM)

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

  $= .102 \leftrightarrow \lambda = 17$

INSIGHTS I 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.