# Physics of strongly coupled Quark-Gluon Plasma (sQGP)


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Berlin-Brandenburg **Akademie der Wissenschaften**,
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# The emerging theory of sQGP

Manybody theory

Strongly coupled cold trapped atoms

Quantum mechanics

Lattice simulations

Quasiparticles
Potentials
correlators

Bound states of EQP and MQP
J/psi,mesons,baryons,calorons

Bose-Einstein Condensation -> confinement

Flux tubes->

sQGP

EoS

Hydrodynamics

RHIC data

Molecular dynamics

Transport properties

Monopoles
E/M duality

Plasma physics

Energy loss,
Collective modes
Mach cones

AdS/CFT duality

String theory

Gauge theories,
SUSY models

# outline, the 3 parts

- 1.The Little Bang: Hydrodynamics of heavy ion collisions, jets and correlations
- 2.Electric-magnetic duality in QCD: monopole plasma and deconfinement transition
- 3.AdS/CFT duality: N=4 plasma and gravity dual of RHIC collisions

# I will have many pictures but not so much text and eqns: one may find them here, archive **0807.3033**

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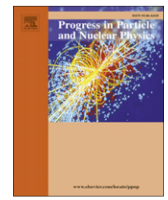


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Review

## Physics of strongly coupled quark–gluon plasma

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A R T I C L E  I N F O

*Keywords:*
Quark–gluon plasma
Finite temperature QCD
Heavy-ion collisions
AdS/CFT

A B S T R A C T

This review covers our current understanding of strongly coupled Quark–Gluon Plasma (sQGP), especially theoretical progress in: (i) explaining the RHIC data by hydrodynamics; (ii) describing lattice data using electric–magnetic duality; (iii) understanding of gauge-string duality known as AdS/CFT and its application for "conformal" plasma. In view of the interdisciplinary nature of the subject, we include a brief introduction into several topics "for pedestrians". Some fundamental questions addressed are: Why is sQGP such a good liquid? What is the nature of (de)confinement and what do we know about "magnetic" objects creating it? Do they play any important role in sQGP physics? Can we understand the AdS/CFT predictions, from the gauge theory side? Can they be tested experimentally? Can AdS/CFT duality help us understand rapid equilibration/entropy production? Can we work out a complete dynamical "gravity dual" to heavy ion collisions?

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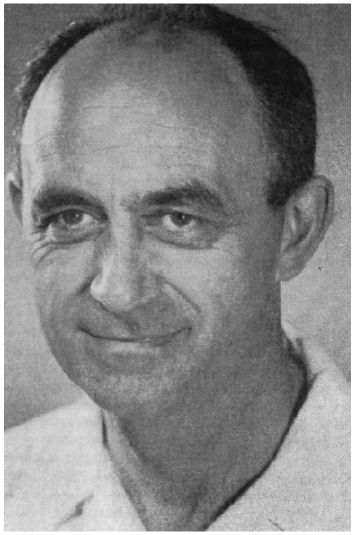
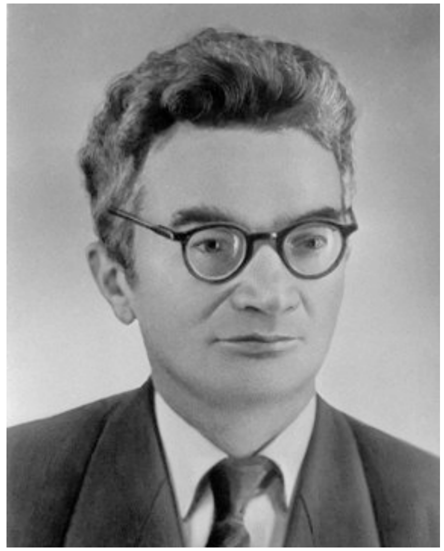
# Thermo and hydrodynamics: can they be used at sub-fm scale?

- Here are three people who asked this question first:
- Fermi (1951) proposed strong interaction leading to equilibration: <n>about $s^{1/4}$
- Pomeranchuck (1952) introduced freezeout
- Landau (1953) explained that one should use hydro in between, saving Fermi's prediction via entropy conservation {he also suggested it should work because coupling runs to strong at small distance! No asymptotic freedom yet in 1950's…}

# From Magdeburg hemispheres (1656) and dreams of 1970's to RHIC

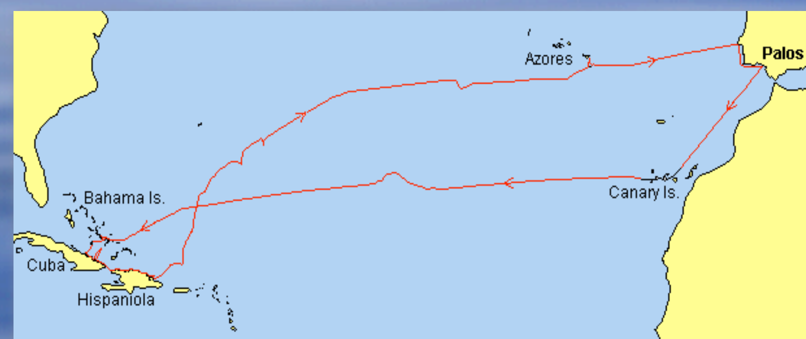

- **"We cannot pump out complicated objects populating the QCD vacuum, but we can pump in something else, namely the Quark-Gluon Plasma, and measure explosion"**

**=> p(QGP)-p(vacuum)**

**(QGP in 1970's was viewed as a simple near-ideal quark-gluon gas, just ``needed to fill the bag")**

One may have an absolutely correct asymptotic theory and still make accidental discoveries...

**Columbus believed if he goes west he should eventually come to India**



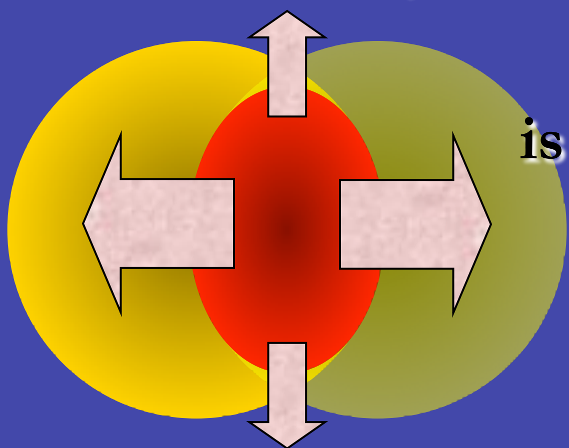

**But something else was on the way...**

**We believed if we increase the energy density, we should eventually get weakly interacting QGP. But something else was found on the way, sQGP**

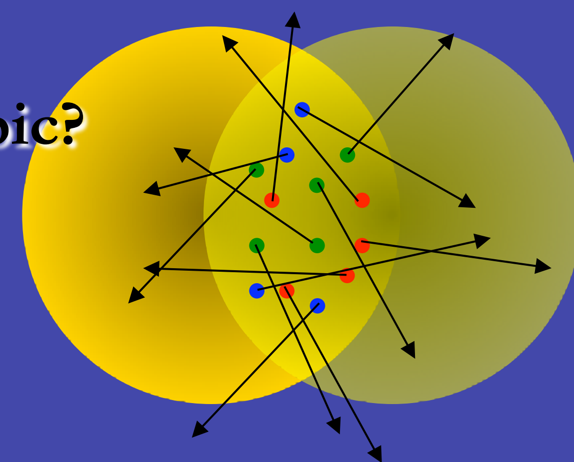
# Contrary to expectations of most, hydrodynamics does work at RHIC!

**Elliptic flow**

How does the system respond to initial spatial anisotropy?

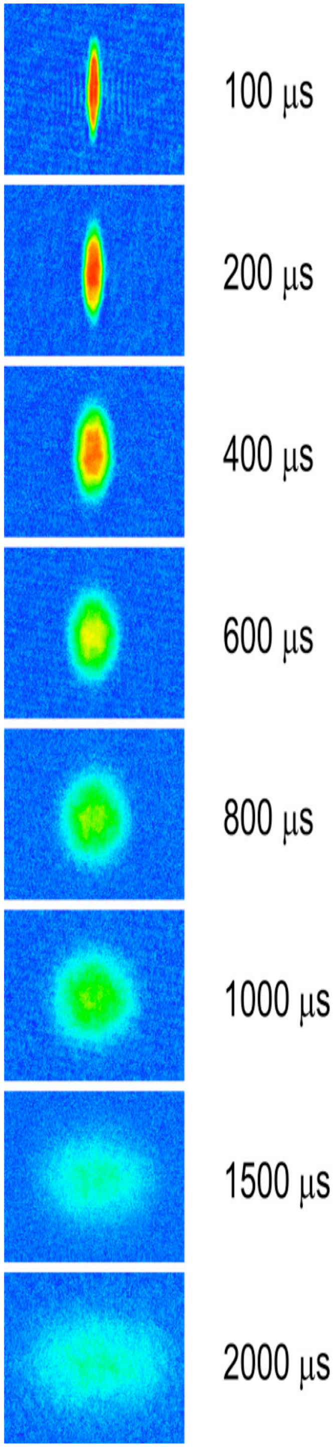


**is it macro or microscopic?**



$$\frac{dN}{p_T dp_T dy d\phi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \cdots\right)$$

$$v_2(p_T, y) = \frac{\int d\phi \cos(2\phi)\frac{dN}{p_T dp_T dy d\phi}}{\int d\phi \frac{dN}{p_T dp_T dy d\phi}} = \langle\cos(2\phi)\rangle$$

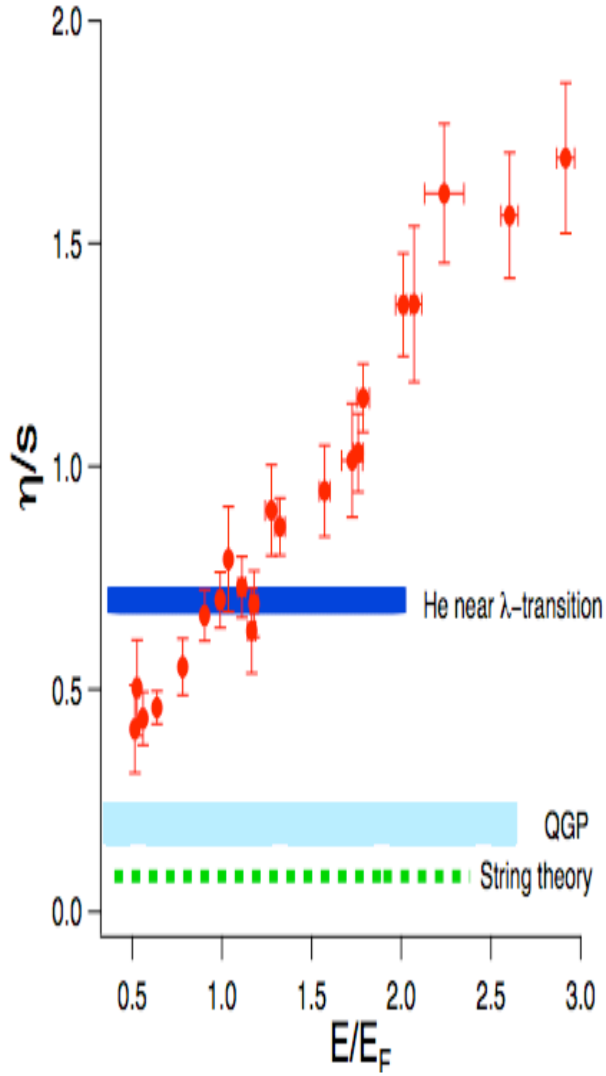



The coolest thing on Earth, T=10 nK or 10^(-12) eV can actually produce a Micro-Bang ! (O'Hara et al, Duke )

**Elliptic flow with ultracold trapped Li6 atoms, a=> infinity regime**

**The system is extremely dilute, but can be put into a hydro regime, with an elliptic flow, if it is specially tuned into a strong coupling regime via the so called Feshbach resonance**

**It makes the ``second best liquid" after sQGP, pushing former champion - liquid He4 near lambda point - to the 3ed place**



# Hydro evolution (Teaney+ES,2001)

- 3 eras – **QGP, mixed** and **hadronic** have about equal timing, 4-5 fm/c each
- except in QGP, expansion is **Hubble-like**

$$\dot{r} = Hr \Longrightarrow r(\tau) = r(0)exp(H\tau)$$

- **The tricky thing is freezeout: when to end hydro**
- **reaction rate= expansion rate**

**(or cascades)**

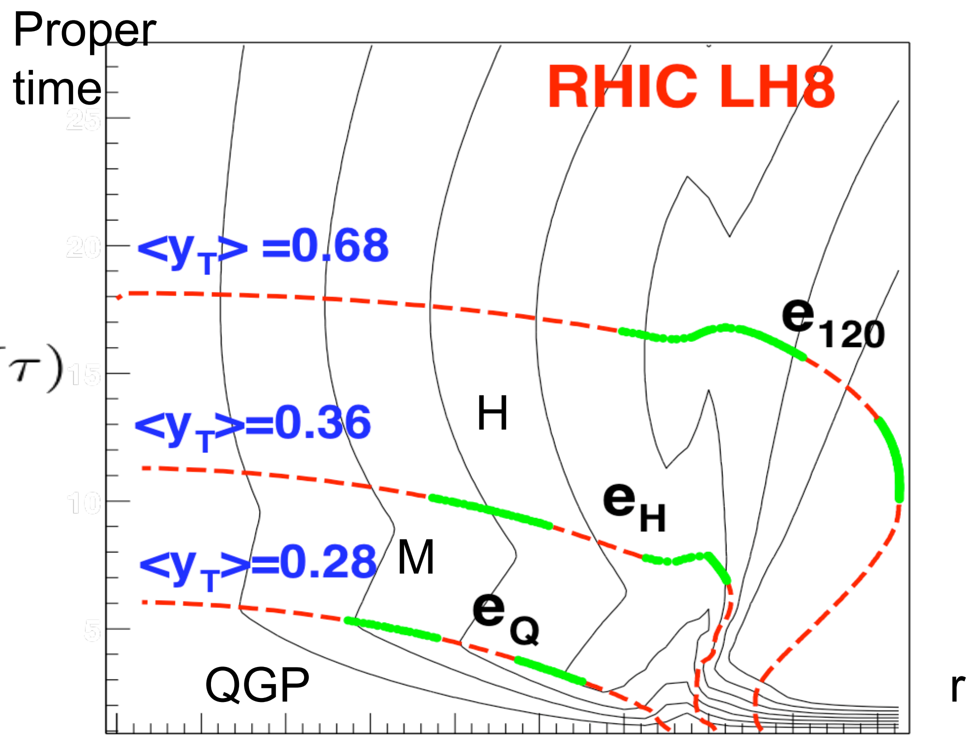


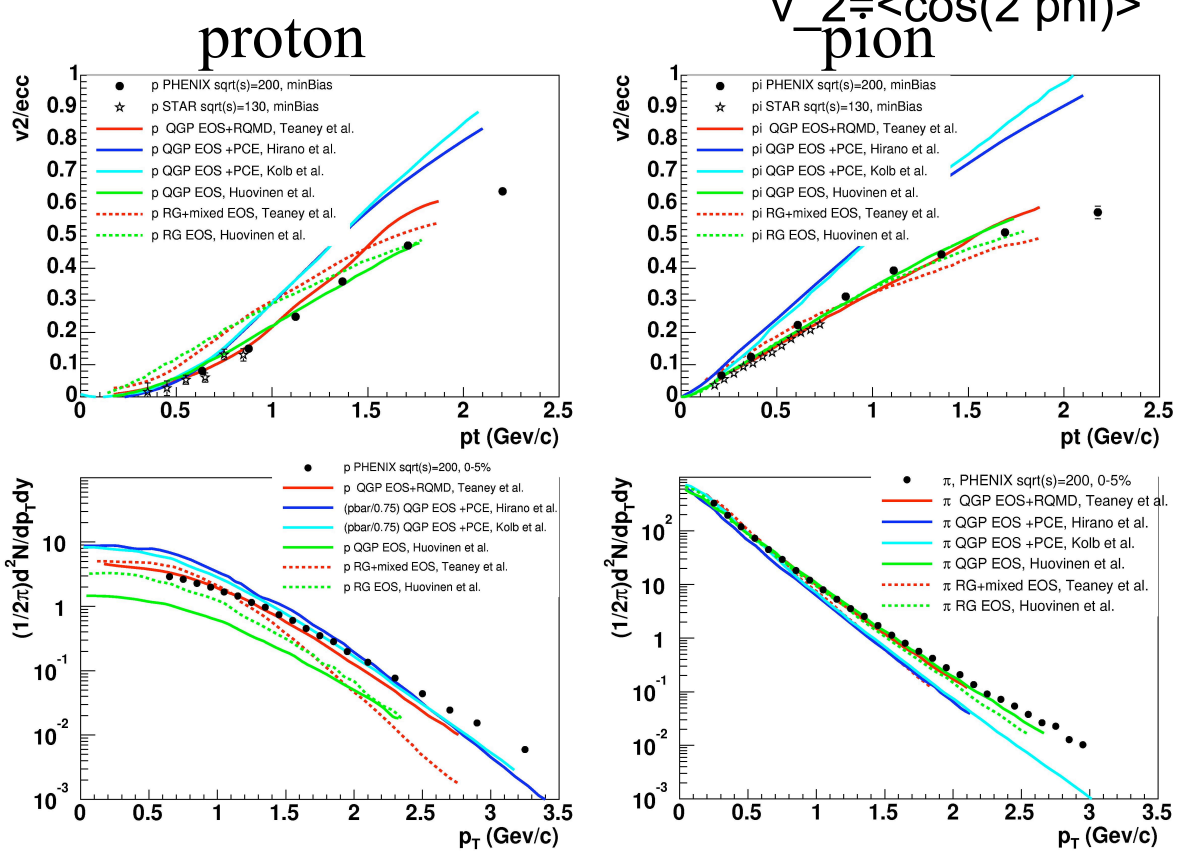

FIG. 2. The hydrodynamic solution for RHIC collision energy, the horizontal axes is the tranverse radius $r$ (each large tick 1 fm), the vertical is proper time (each small tick 1 fm).

## 2001-2005: hydro describes radial and elliptic flows for all secondaries , pt<2GeV, centralities, rapidities, A (Cu,Au)…

Experimentalists were very sceptical but were convinced and ``near-perfect liquid” is now official,

=>AIP declared this to be discovery #1 of 2005 in physics

v_2=<cos(2 phi)>




**PHENIX, Nucl-ex/0410003**

red lines are for ES +Lauret+Teaney done before RHIC data, never changed or fitted, describes SPS data as well! It does so because of the correct hadronic matter /freezout via (RQMD)

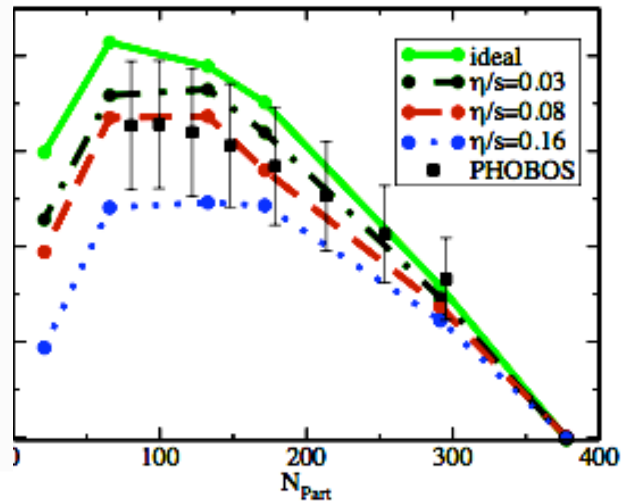
**Viscosity Information from Relativistic Nuclear Collisions: How Perfect is the Fluid Observed at RHIC?**

Paul Romatschke[1] and Ulrike Romatschke[2]

[1] *Institute for Nuclear Theory, University of Washington, Box 351550, Seattle, WA, 98195, USA*
[2] *Department of Atmospheric Sciences, University of Washington, Box 351640, Seattle, WA, 98195, USA*

(Dated: October 26, 2007)

Relativistic viscous hydrodynamic fits to RHIC data on the centrality dependence of multiplicity, transverse and elliptic flow for $\sqrt{s}$ = 200 GeV Au+Au collisions are presented. For standard (Glauber-type) initial conditions, while data on the integrated elliptic flow coefficient $v_2$ is consistent with a ratio of viscosity over entropy density up to $\eta/s \simeq 0.16$, data on minimum bias $v_2$ seems to favor a much smaller viscosity over entropy ratio, below the bound from the AdS/CFT conjecture. Some caveats on this result are discussed.




$$
\begin{aligned}
(\epsilon + p) D u^\mu &= \nabla^\mu p - \Delta^\mu_\alpha d_\beta \Pi^{\alpha\beta}\,, \\
D\epsilon &= -(\epsilon + p)\nabla_\mu u^\mu + \frac{1}{2}\Pi^{\mu\nu}\langle \nabla_\nu u_\mu \rangle\,, \\
\Delta^\mu_\alpha \Delta^\nu_\beta D\Pi^{\alpha\beta} &= -\frac{\Pi^{\mu\nu}}{\tau_\Pi} + \frac{\eta}{\tau_\Pi}\langle \nabla^\mu u^\nu \rangle - 2\Pi^{\alpha(\mu}\omega^{\nu)}_{\ \alpha} \\
&\quad + \frac{1}{2}\Pi^{\mu\nu}\left[5 D \ln T - \nabla_\alpha u^\alpha\right], \qquad (
\end{aligned}
$$

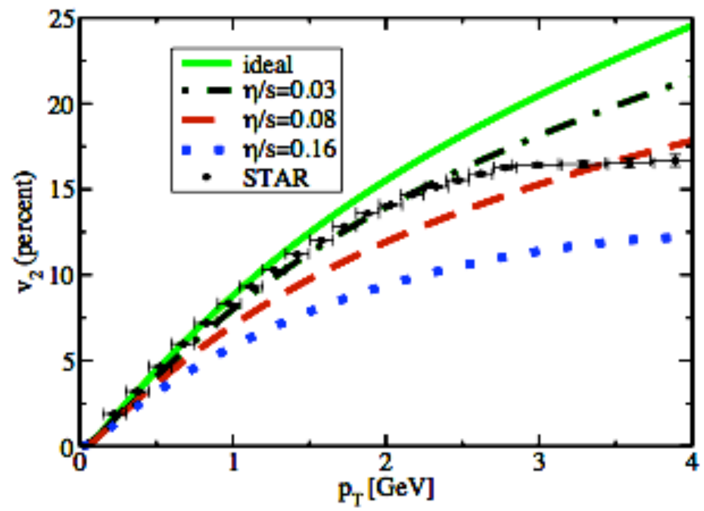



FIG. 3: PHOBOS [24] data on $p_T$ integrated $v_2$ and STAR [25] data on minimum bias $v_2$, for charged particles in Au+Au collisions at $\sqrt{s} = 200$ GeV, compared to our hydrodynamic model for various viscosity ratios $\eta/s$. Error bars for PHOBOS data show 90% confidence level systematic errors while for STAR only statistical errors are shown.

So it is **even less than presumed**

**Lower bound (Son et al) >1/4π!**

Why it may be possible, read Lublinsky,ES hep-ph0704.1647

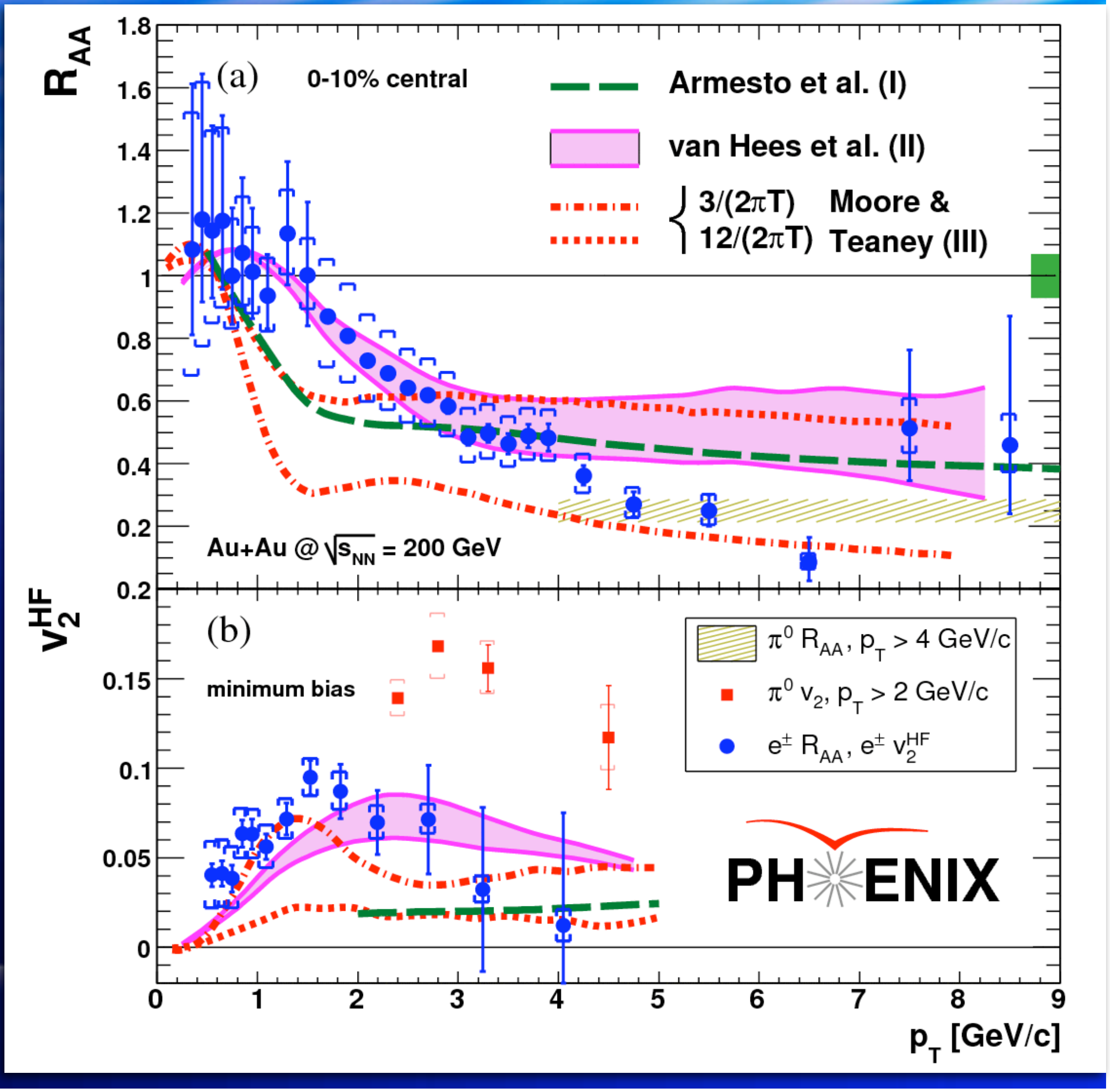
# More major surprises from RHIC: strong jet quenching and flow of heavy quarks

nucl-ex/0611018

Heavy quark quenching as strong as for light gluon-q jets!

Radiative energy loss only fails to reproduce $v_2^{HF}$.

Heavy quark elliptic flow: $v_2^{HF(pt<2GeV)}$ is about the same as for all hadrons!
=>
**Small relaxation time $\tau$ or diffusion coefficient $D_{HQ}$ inferred for charm.**

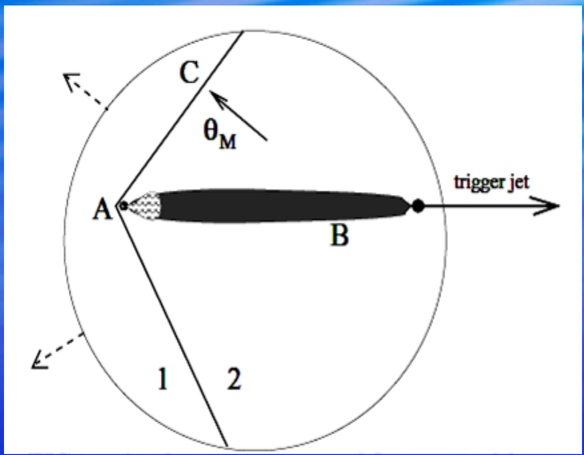


# Sonic boom from quenched jets

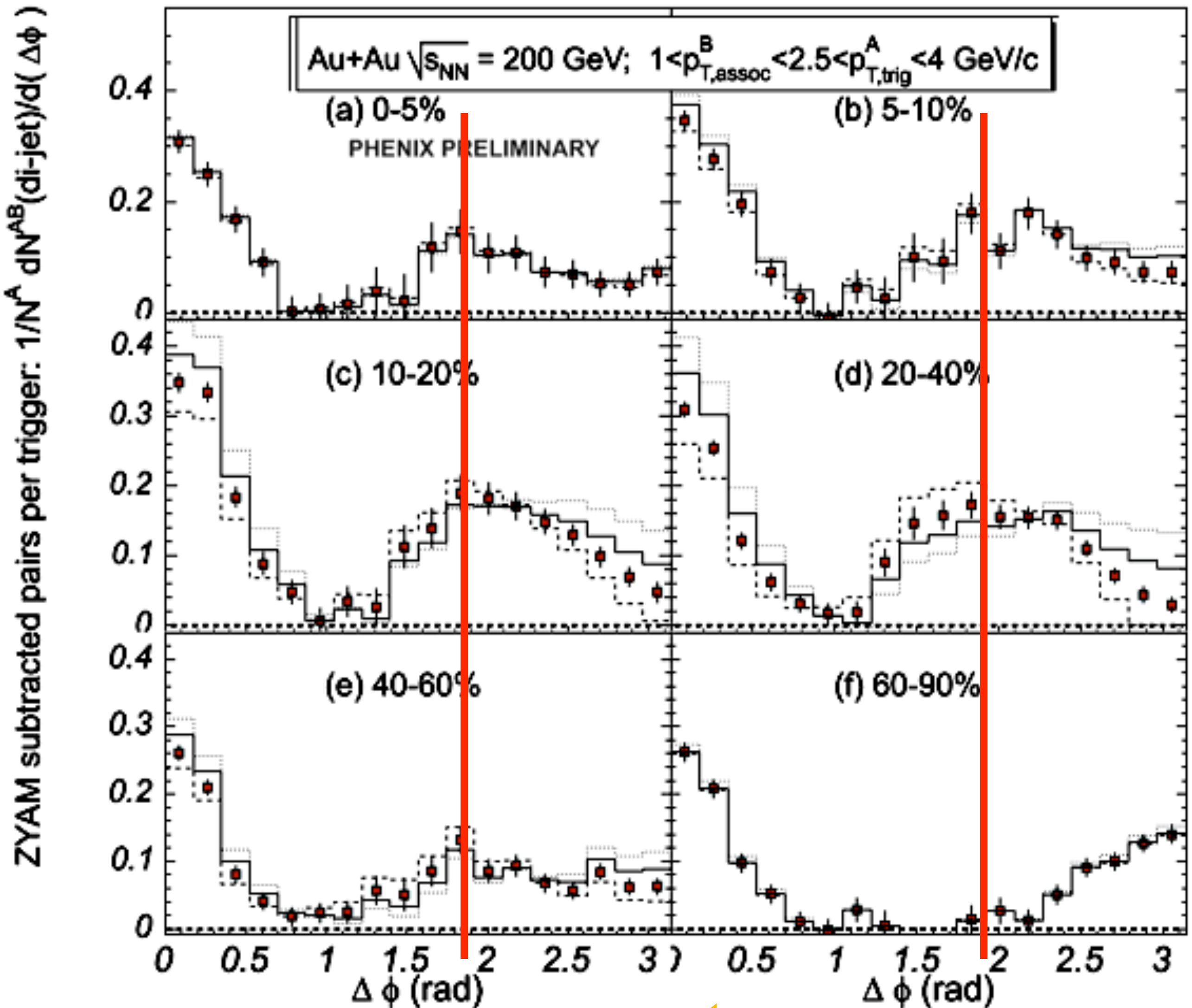
Casalderrey,ES,Teaney, hep-ph/0410067; H.Stocker…

- the energy deposited by jets into liquid-like strongly coupled QGP must go into conical shock waves
- We solved relativistic hydrodynamics and got the flow picture

Wake effect or "sonic boom"




# PHENIX jet pair distribution




Note: it is only projection of a cone on phi

Note 2: there is also a minimum in

<p_t(\phi)> at

180 degr., with

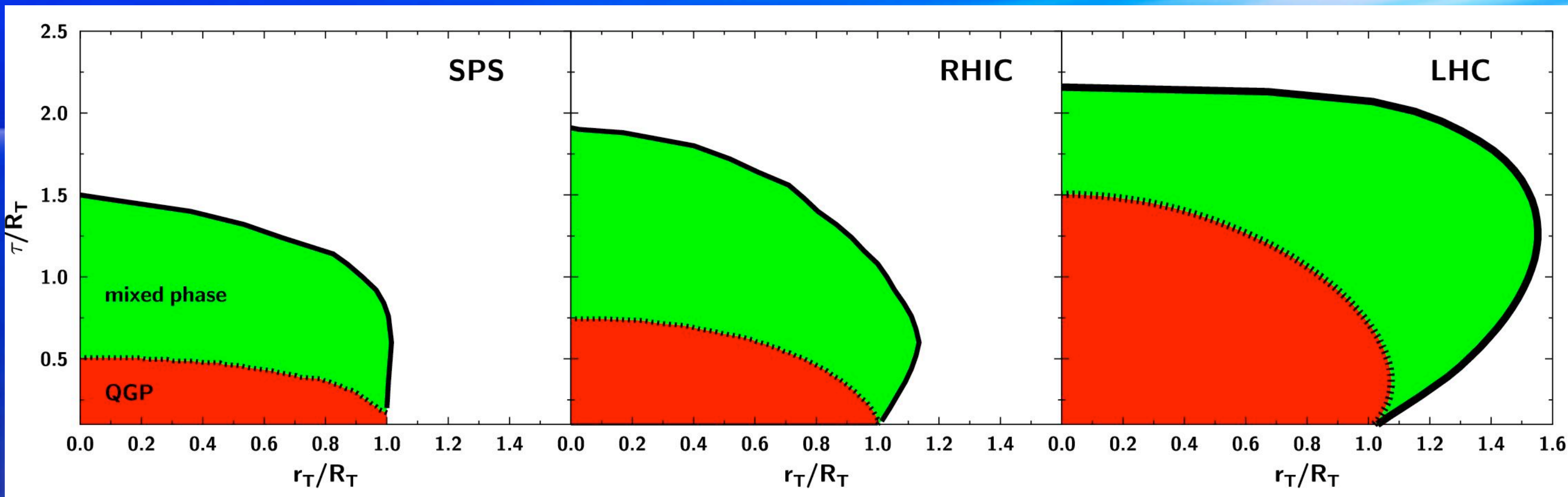
a value

Consistent with

background

The most peripheral bin, here there is no QGP

# From SPS to LHC




**•1 bn$ question: would it be a good liquid at LHC?**

• lifetime of QGP phase nearly doubles, but v2 grows only a little, to a universal value corresponding to EoS p=(1/3)epsilon

• radial flow grows by about 20% => less mixed / hadronic phase (only 33% increase in collision numbers of hadronic phase in spite of larger multiplicity)

(hydro above from S.Bass)

# Summary of part 1

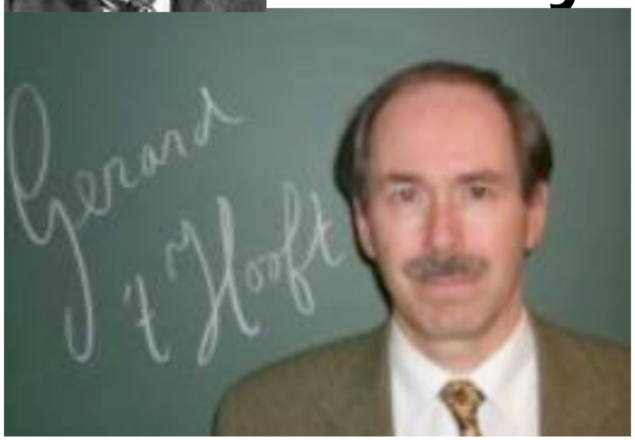
RHIC experiments observes the ``Little Bang", with equal time (5 fm/c) spent in three eras, QGP, M and H

Radial and elliptic flow, as a function of particle type, collision energy, rapidity, transverse momentum, centrality and A are well explained by (near) ideal hydrodynamics with lattice-based equation of state. The phase transition is important

Matter observed at RHIC is the best liquid known! Eta/s <0.2

Jets, including c and b quarks have strong quenching.
Their energy go into some collective conical structure

# Magnetic objects and their dynamics: classics




- Dirac explained how magnetic charges may coexists with quantum mechanics (1934)
- ‘t Hooft and Polyakov discovered **monopoles** in Non-Abelian gauge theories (1974)
- ‘t Hooft and Mandelstamm suggested “dual superconductor” mechanism for confinement (1982)
- Seiberg and Witten shown how it works, in the **N=2 Super -Yang-Mills theory (1994)**

Liao,ES hep-ph/0611131

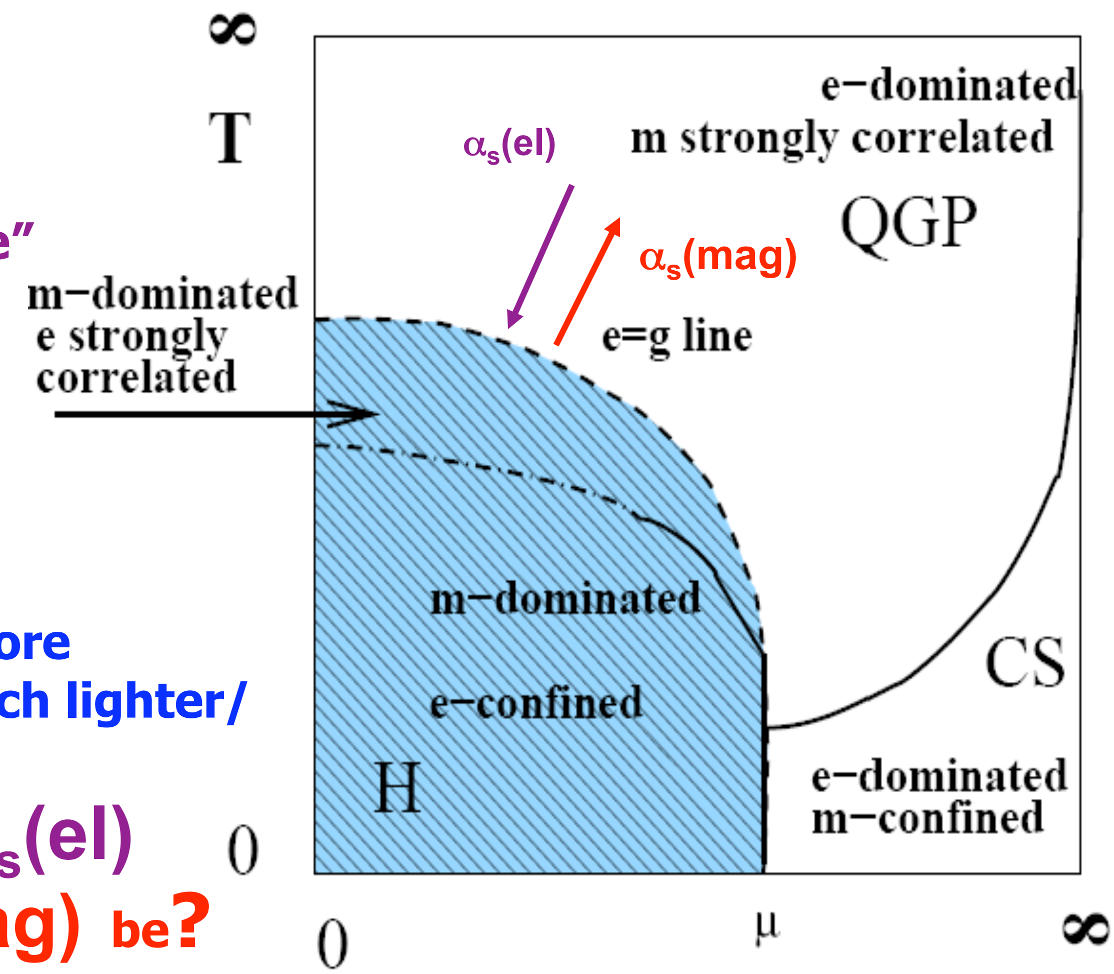
electric/magnetic couplings (e/g)

run in the **opposite directions!**

**$\alpha_s$(electric) $\alpha_s$(magnetic)=1**

**Old good Dirac condition**
**(in QED-type units $e^2 = \alpha_s$)**

**at the e=g "equilibrium line"**
**$\alpha_s$(el)= $\alpha_s$(mag) =1**
**(the best liquid there?)**




**monopoles gets dominant before deconfinement, as they are much lighter/ denser than gluons/quarks**

**=>$\alpha_s$(mag) smaller than $\alpha_s$(el)**

**how small can $\alpha_s$(mag) be?**

# Electric and magnetic screening masses (inverse screening lengths) from numerical simulation in lattice gauge theory

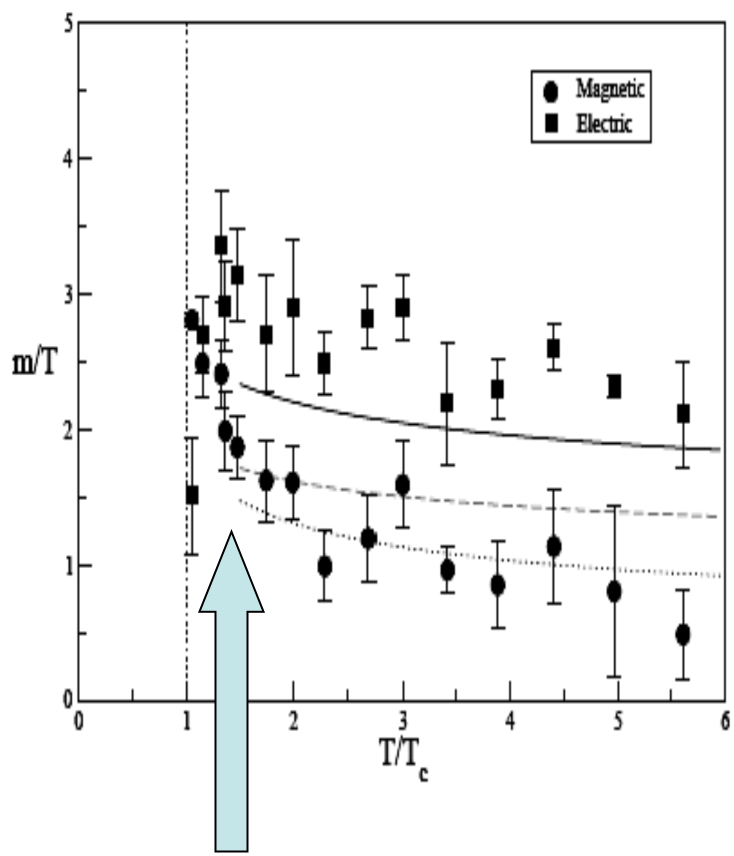
Nakamura et al, 2004

arrow shows **the ``self-dual" E=M point**

**Me<Mm**
**Magnetic**
**Dominated**

**At T=0 magnetic**
**Screening mass**
**Is about 2 GeV**
**(de Forcrand et al)**
**(a glueball mass)**

**(Other lattice data**
**-Karsch et al-**
**show how Me**
**Vanishes at Tc**
**better)**




**Me>Mm**
**Electrric**
**dominated**

$M_E/T=O(g)$
ES 78
$M_M/T=O(g^2)$
Polyakov 79

**Why is QGP getting magnetic as T=>Tc?**

GEF-TH 22/07

Magnetic monopoles in the high temperature phase of Yang–Mills theories

Spring 2008

A. D'Alessandro and M. D'Elia*
*Dipartimento di Fisica, Università di Genova and INFN, Sezione di Genova, Via Dodecaneso 33, I-16146 Genova, Italy*

**x-Correlations show it is a liquid => Magnetic Coulomb coupling**

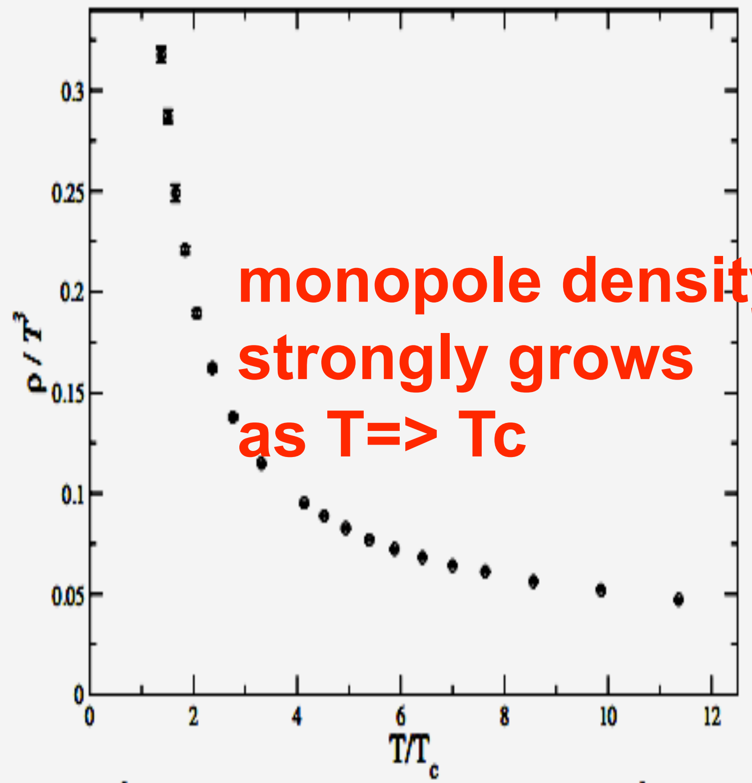



FIG. 3. $\rho(T)/T^3$ as a function of $T/T_c$. Data have been obtained on a $48^3 \times L_t$ lattice, with variable $L_t$ and at $\beta = 2.75$ (first 9 points), and variable $\beta$ at $L_t = 4$ (last 10 points).

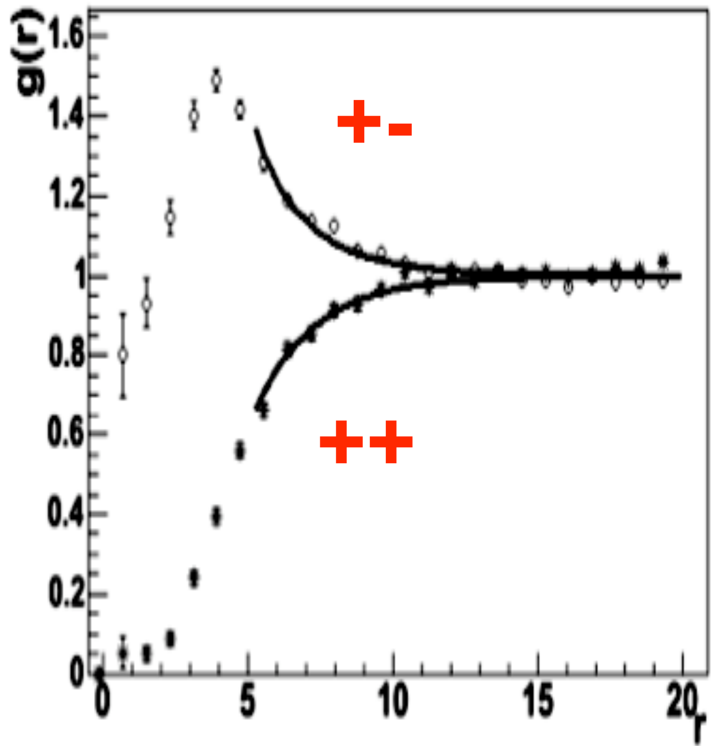



FIG. 5. $g(r)$ for the monopole-monopole (stars) and monopole-antimonopole (circles) case on $0^3 \times 5$ lattice at $\beta = 2.7$ ($T \simeq 2.85\ T_c$). The reported curves correspond to fits according to $) = \exp(-V(r)/T)$ with $V(r)$ a Yukawa potential (see Eqs. (2.9) and (2.10)).

Lattice SU(2) gauge theory, monopoles found and followed by Min.Ab.gauge

# Magnetic Component of Quark-Gluon Plasma is also a Liquid!

Jinfeng Liao and Edward Shuryak
*Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794*
(April 1, 2008)

The so called magnetic scenario recently suggested in [1] emphasizes the role of monopoles in strongly coupled quark-gluon plasma (sQGP) near/above the deconfinement temperature, and specifically predicts that they help reduce its viscosity by the so called "magnetic bottle" effect. Here we present results for monopole-(anti)monopole correlation functions from the same classical molecular dynamics simulations, which are found to be in very good agreement with recent lattice results [2]. We show that the magnetic Coulomb coupling does run in the direction *opposite* to the electric one, as expected, and it is roughly inverse of the asymptotic freedom formula for the electric one. However, as $T$ decreases to $T_c$, the magnetic coupling never gets weak, with the plasma parameter always large enough ($\Gamma > 1$). This nicely agrees with empirical evidences from RHIC experiments, implying that magnetic objects cannot have large mean free path and should also form a good liquid

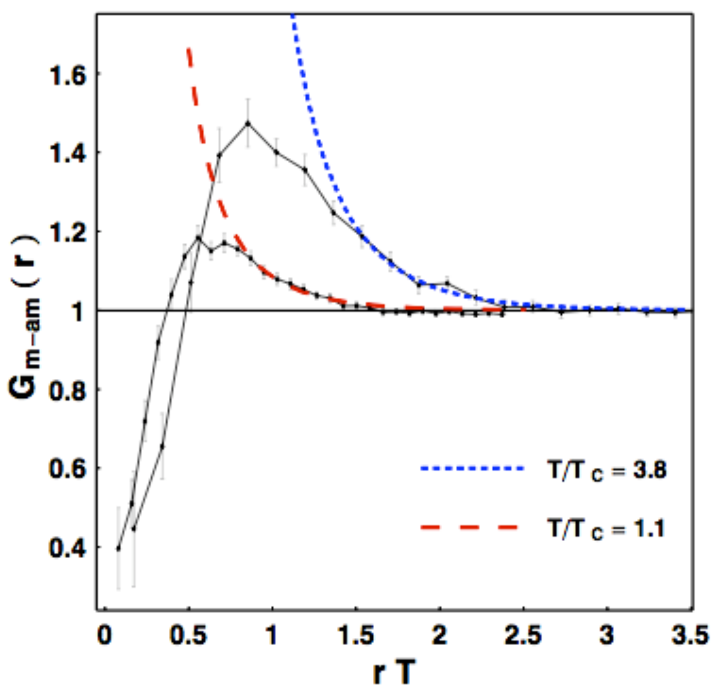
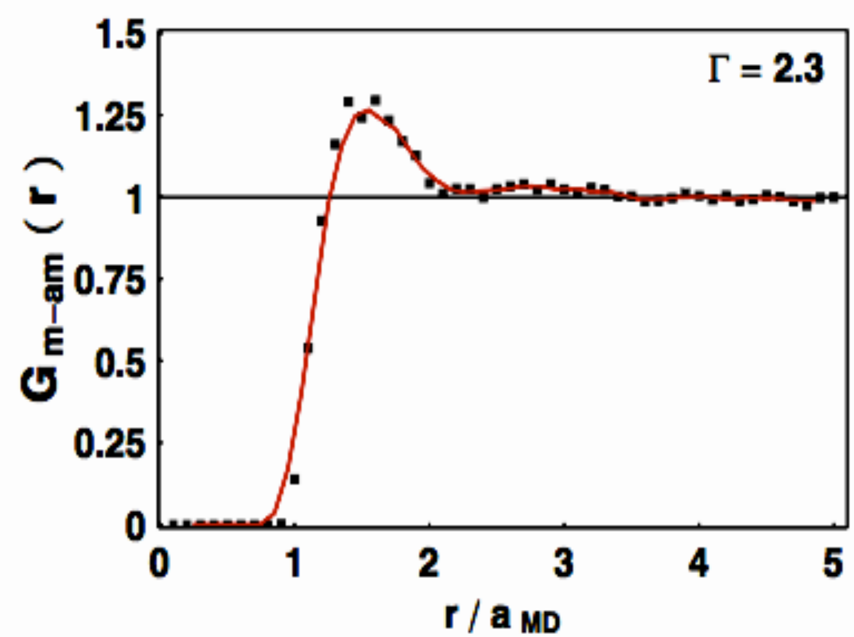



FIG. 2. (color online) Monopole-antimonopole correlators versus distance: points are lattice data [2], the dashed lines are our fits.

Our MD for 50-50 MQP/EQP



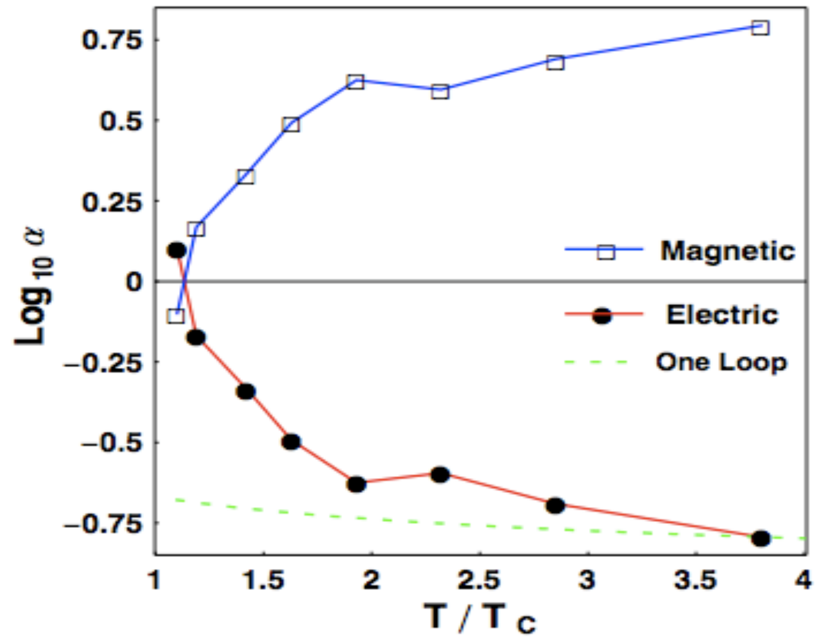
## $\alpha_s$(electric) and $\alpha_s$(magnetic)

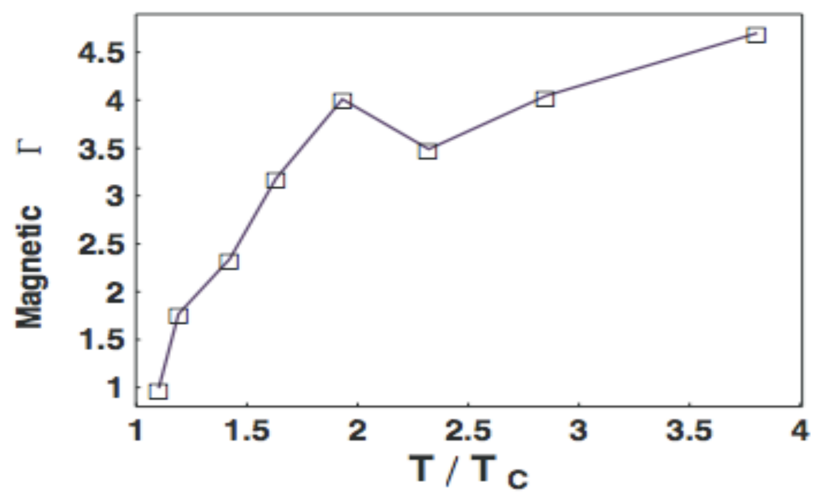
## do run in opposite directions!

- Squares: fitted magnetic coupling, circles: its inverse compared to asymptotic freedom (dashed)
- Effective plasma parameter (here for magnetic)

$$\Gamma \equiv \frac{\alpha_C / (\frac{3}{4\pi n})^{1/3}}{T}$$

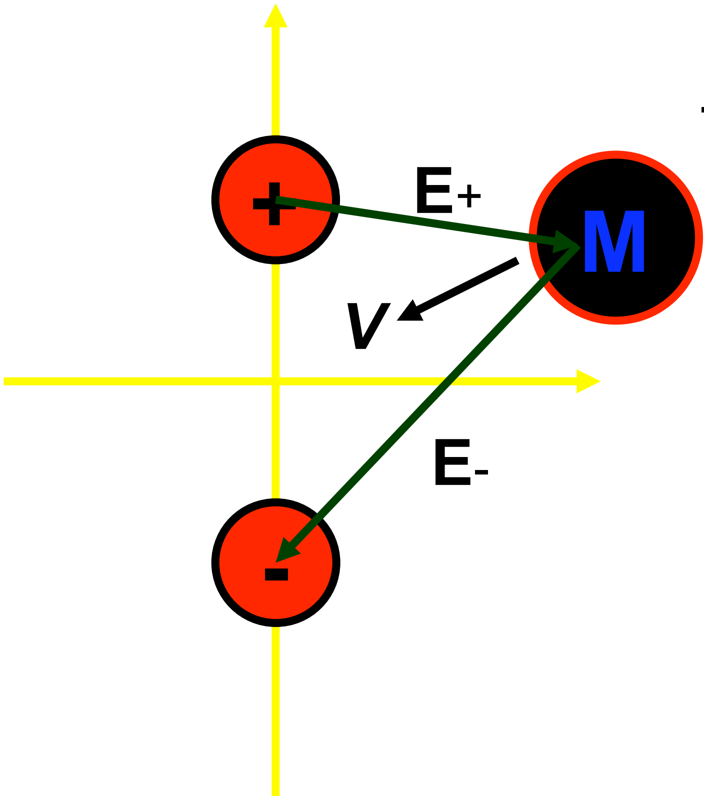
- So, the monopoles are **never weakly coupled!**
- **(just enough to get Bose-condenced)**



# *So why are collisions so often in*❄❄❄ *sQGP making it the best liquid?*

# ***Because of magnetic bottle effect:***




*static eDipole+MPS*

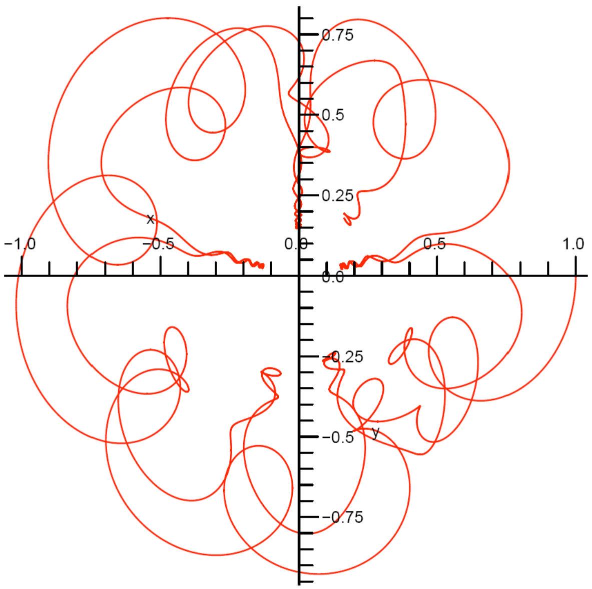
Note that Lorentz force is O(v)!

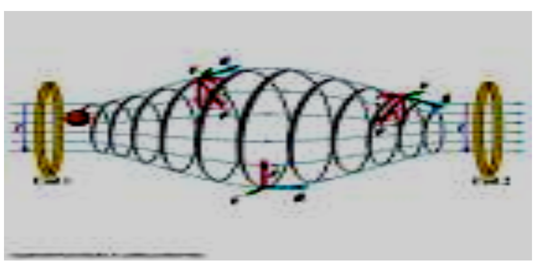
$$M\frac{d^2\vec{r}}{dt^2} = \frac{g}{c}\vec{E}\times\frac{d\vec{r}}{dt}$$

$$\vec{E} = e\left[\frac{\vec{r}-a\vec{z}}{|\vec{r}-a\vec{z}|^3} - \frac{\vec{r}+a\vec{z}}{|\vec{r}+a\vec{z}|^3}\right]$$

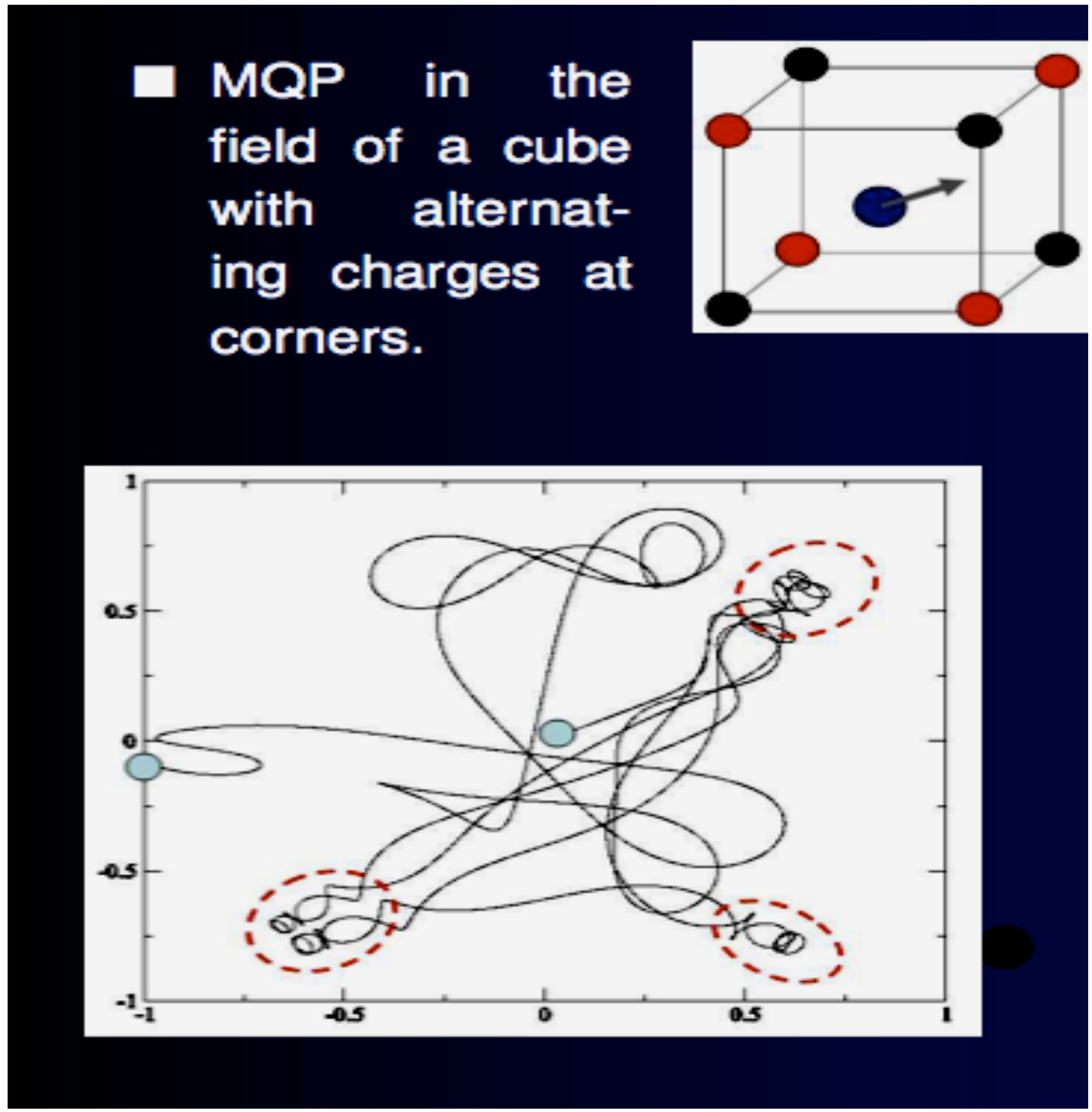
Monopole rotates around the electric field line, bouncing off both charges (whatever the sign)

## **two charges** play ping-pong with a monopole without even moving!



**Dual to magnetic bottle**

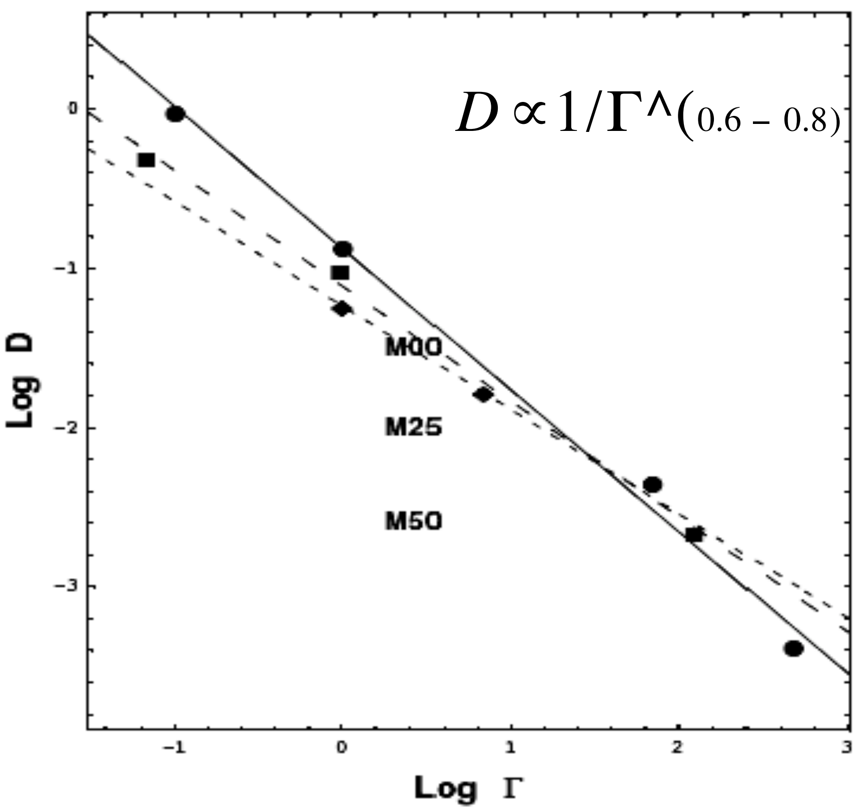


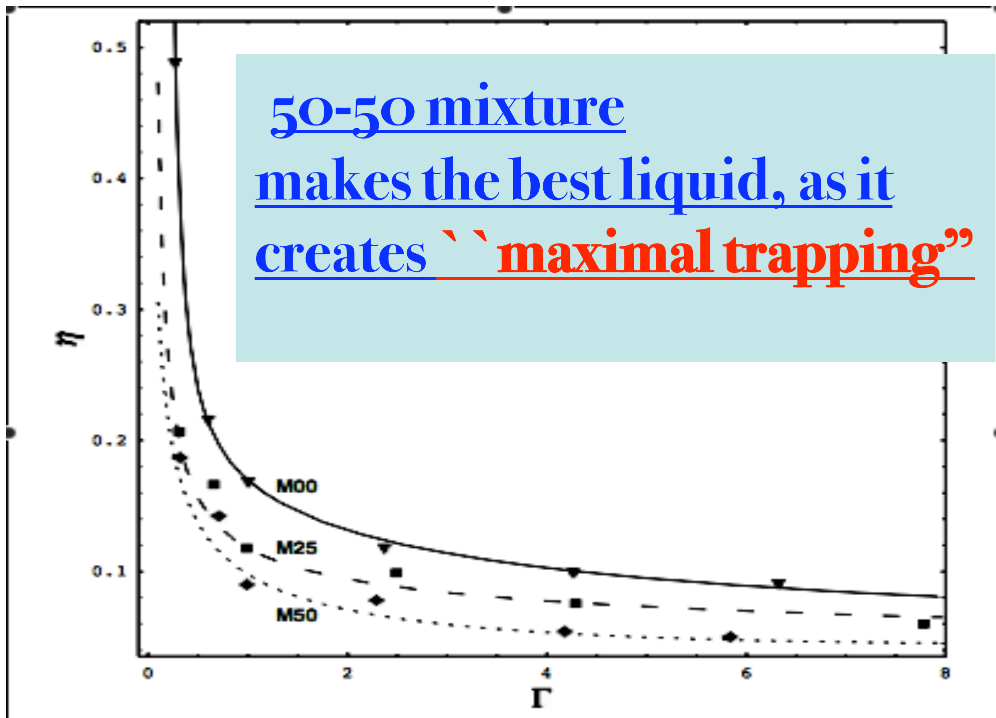
# MD simulation for novel plasma containing both charges and monopoles (Liao,ES hep-ph/ 0611131)

monopole admixture up to M50=50% , 1000 particles, numerically solved

ses indefinitely, viscosity does not

$$D(\tau) = \frac{1}{3N} < \sum_{i=1}^{N} \vec{v}_i(\tau) \cdot \vec{v}_i(0) >$$




**50-50 mixture makes the best liquid, as it creates ``maximal trapping”**

FIG. 16. Shear viscosity $\eta$ calculated at different plasma parameter $\Gamma$ for M00(circle), M25(square), and M50(diamond) plasma respectively.

# Monopoles in electric Quark-Gluon Plasma

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November 24, 2008

- Quantum problem of gluon-monopole scattering
- n=eg (=1) is the only parameter, if we ignore the monopole core and keep only Coulomb B field

We denote the vector harmonics by $\Phi^{m,\sigma}_{j,n}(\theta,\varphi)_{ai}$. They obey the following eigenvalue equations

$$\left\{\begin{array}{l} \vec{J}^2 \\ J_3 \\ (\hat{r}\cdot\vec{I}) \\ (\hat{r}\cdot\vec{S}) \end{array}\right\}\Phi^{m,\sigma}_{j,n}(\theta,\varphi)_{ai} = \left\{\begin{array}{l} j(j+1) \\ m \\ n \\ \sigma \end{array}\right\}\Phi^{m,\sigma}_{j,n}(\theta,\varphi)_{ai}. \tag{55}$$

$$\begin{aligned}\phi^{(+)}(\vec{r}) &= e^{-i\pi n}\sum_{j=|n|}^{j_{max}}(2j+1)e^{i\pi j}e^{-i\pi j'/2}j_{j'}(kr)\left[U(-\varphi,\theta,\varphi)\,\chi^n_i\right]\mathcal{D}^{(j)}_{n,-n}(-\varphi,\theta,\varphi) \\ &= \left[U(-\varphi,\theta,\varphi)\,\chi^n_i\right]\psi^{(+)}(\vec{r}). \end{aligned} \tag{91}$$

We recall that the index $j'$ in the above formula is the positive root of

$$j'(j'+1) = j(j+1) - n^2. \tag{92}$$

j' is not an integer!

# A surprize: no corrections to thermodynamics

$$\delta M_m = \frac{T}{\pi} \sum_j (2j+1) \int dk \frac{d\delta_j}{dk} f(k,T)$$

- Beth-Uhlenbeck correction (extra states in a box) is zero because there is no dependence on k

The origin of this somewhat unexpected result can be traced to the fact that the Beth-Uhlenbeck expression was derived from a semiclassical counting of the density of states in a large (spherical) box containing the monopole. However the semiclassical density of states, related to classical phase space, is insensitive to magnetic fields because the corresponding integral

$$\Omega_{cl}(E) = \int \frac{d^3p d^3x}{(2\pi)^3} \delta\left(E - H(p,x)\right) \tag{82}$$

for an electric particle in any magnetic field $H = (\vec{p} - e\vec{A}(x))^2/2m$ does not depend on the field at all (in order to see that this explanation is correct, consider for

# Not surprising, large correction to transport

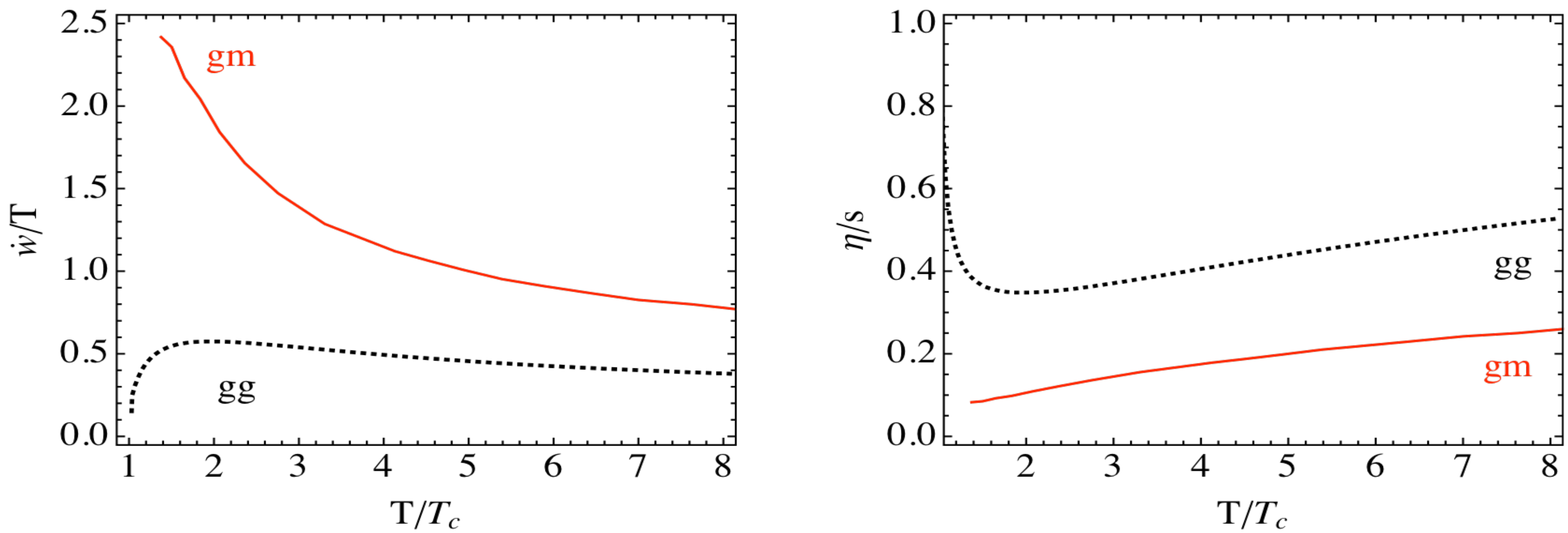



Figure 14: Left panel: gluon-monopole and gluon-gluon scattering rate. Right panel: gluon-monopole and gluon-gluon viscosity over entropy ratio, $\eta/s$.

- **RHIC: T/Tc<2, LHC T/Tc<4**: we predict hydro will still be there, with η/s about .2

# Summary of part 2

Classics: dual superconductor…. N=2 SYM: as T decreases,
electric coupling grows and magnetic decreases

At 1< T<1.4 Tc electric plasma (q,g) becomes magnetic (mono+dyons)

Monopole density peak near Tc where they become as light as 200 MeV
While q,g and dyons are all heavier, around 500-800 MeV. They behave
Like Coulomb plasma with coupling **<u>in</u>**creasing with T

Scattering between e- and m-charges is large backward, due to Lorentz force
Classical trapping => small viscosity and diffusion
Quantum g+m scattering as example produces reasonable viscosity eta/s

Monopoles peak near Tc and seem to be Bose-condenced similar to He4

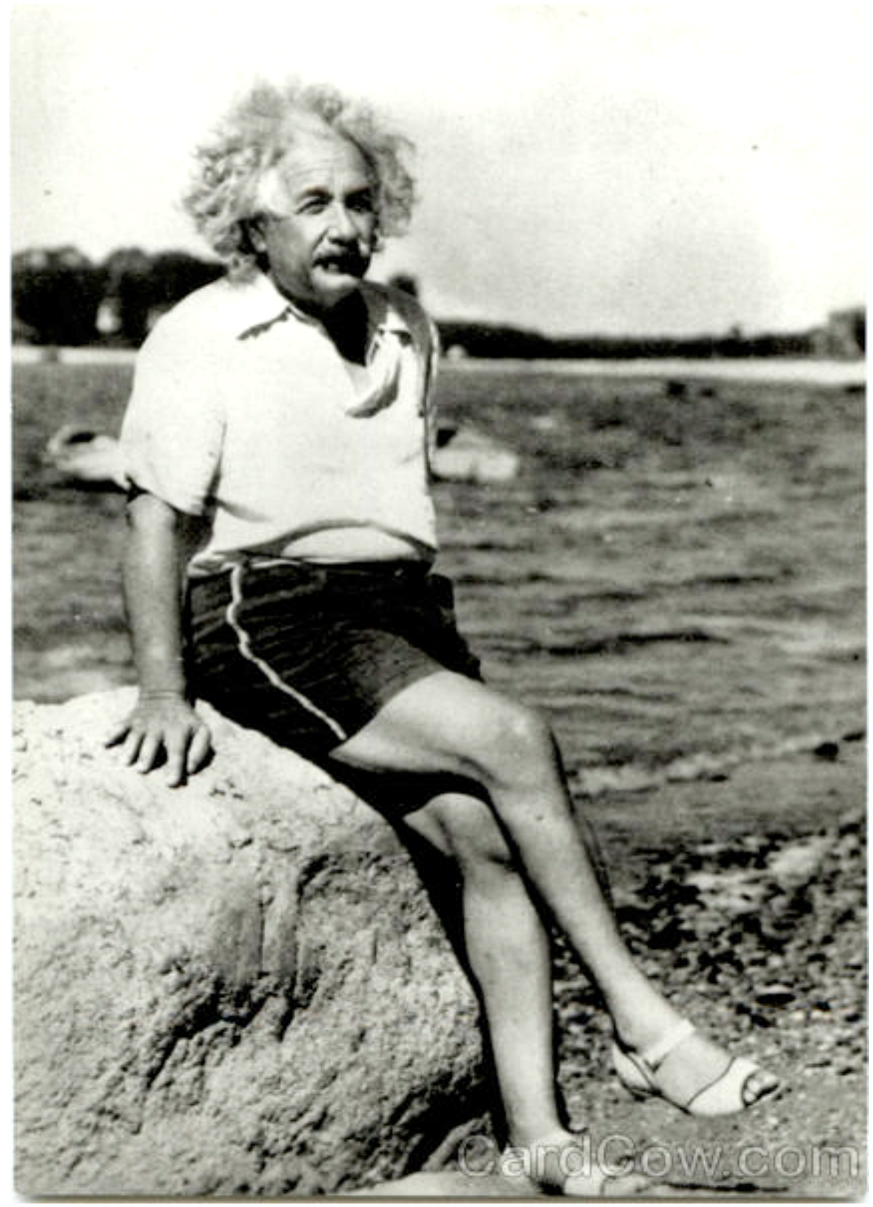
# Einstein

- Why this picture?

=> Going to discuss general relativity-based problem it is hard not to think of him

⇒Being in Einstein hall

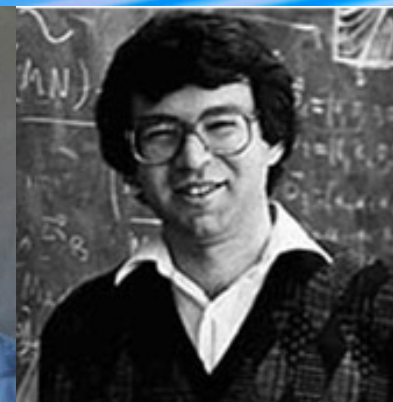
⇒I found his picture at the **Stony Brook beach** where he  rented for few summers, not for science (there were no University then) but to **practice sailing,** which he learned on the Berlin's lakes…



# The first gauge-string duality AdS/CFT, found in 1997!







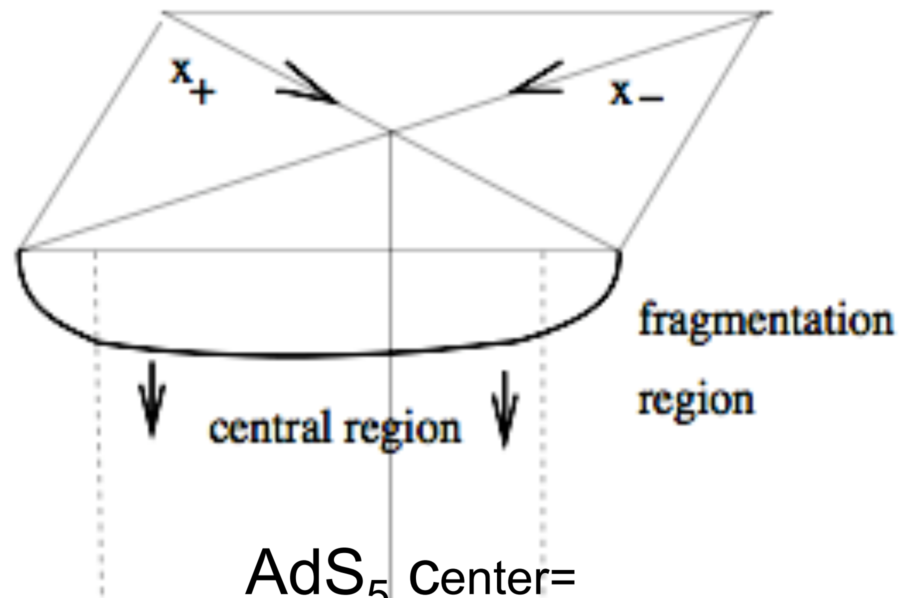
- AdS/CFT correpondence or ``Maldacena duality" was found on the long path illuminated by Witten, Polyakov, Polchinski, Klebanov…

# Gravity dual to the (e+e-=>heavy quarks) collision: "Lund model" in AdS/CFT

(Shu Lin,ES, I+II papers )

If colliding objects are made of heavy quarks

- **Stretching strings** are falling under the AdS gravity and don't break
- **Instability** of simple scaling solution and numerical studies
- Analogs of longitudinal E,B in wGLASMA




$AdS_5$ Center= Extremal b.h.

Toward the AdS/CFT Gravity Dual for High Energy Collisions:
II. The Stress Tensor on the Boundary

Shu Lin and Edward Shuryak

*Department of Physics and Astronomy, Stony Brook University , Stony Brook NY 11794-3800, USA*

(Dated: November 25, 2007)

In this second paper of the series we calculate the stress tensor of excited matter, created by "debris" of high energy collisions at the boundary. We found that massive objects ("stones") falling into the AdS center produce gravitational disturbance which however has *zero* stress tensor at the boundary. The falling open strings, connected to receeding charges, do produce a nonzero stress tensor which we found analytically from time-dependent linearized Einstein equations in the bulk. It corresponds to exploding non-equilibrium matter: we discuss its behavior in some detail, including its internal energy density in a comoving frame and the "freezeout surfaces". We then discuss what happens for the ensemble of strings.

- a ``**holographic image**" of this process,
- <= time-dependent Green function for linearized Einstein eqns

**How does it look for a falling string?**

**Is it hydro-like explosion or not?**

- Holographic image a falling string show **an explosio**
- *(as far as we know the fi time-dependent hologramm)*
- **Which however cannot be reprensented as hydro fluid! => anisotropic pressure in the ``comoving frame”**
- **(like in Raju’s wGLASMA)**

$T_{00}$ , $T_{oi}$

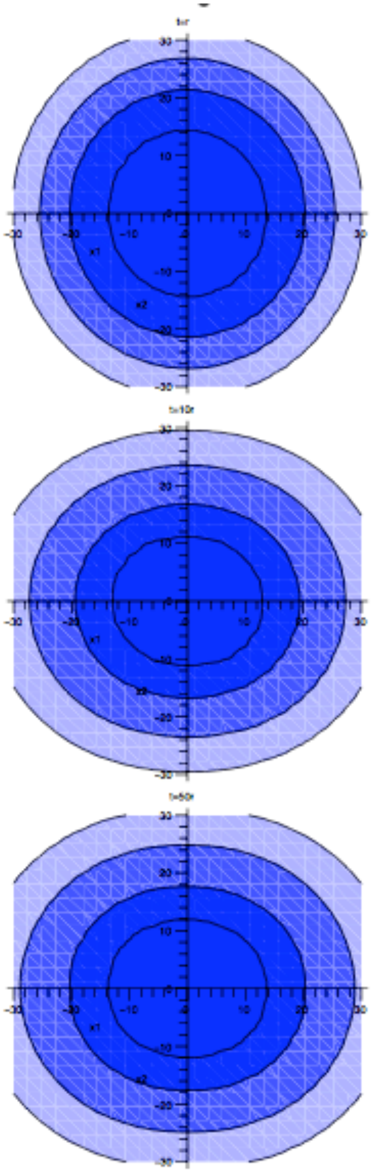


FIG. 1: (color online) The contours of energy density $T^{00}$, in unit of $\frac{2\sqrt{\lambda}}{f_0^3 \pi^2}$, in $x_1 - x_2$ plane at different time. The three plots are made for $t = r$, $t = 10r$ and $t = 50r$ from top to bottom. The magnitude of $T^{00}$ is represented by the color,

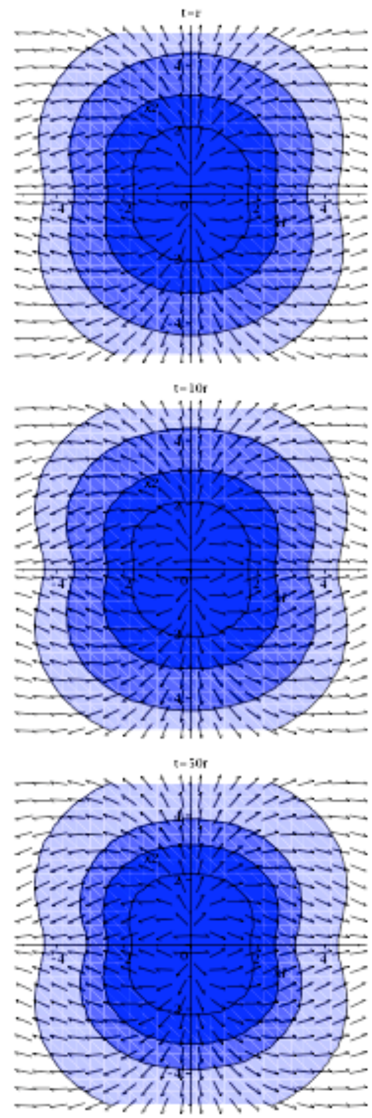


FIG. 2: (color online)The contours of momentum den sity $T^{0i}$, in unit of $\frac{2\sqrt{\lambda}}{f_0^3 \pi^2}$, in $x_1 - x_2$ plane at differen time. The three plots are made for $t = r$, $t = 10$ and $t = 50r$ from top to bottom. The magnitude i represented by color, with darker color corresponding t greater magnitude. The corresponding contour values ar

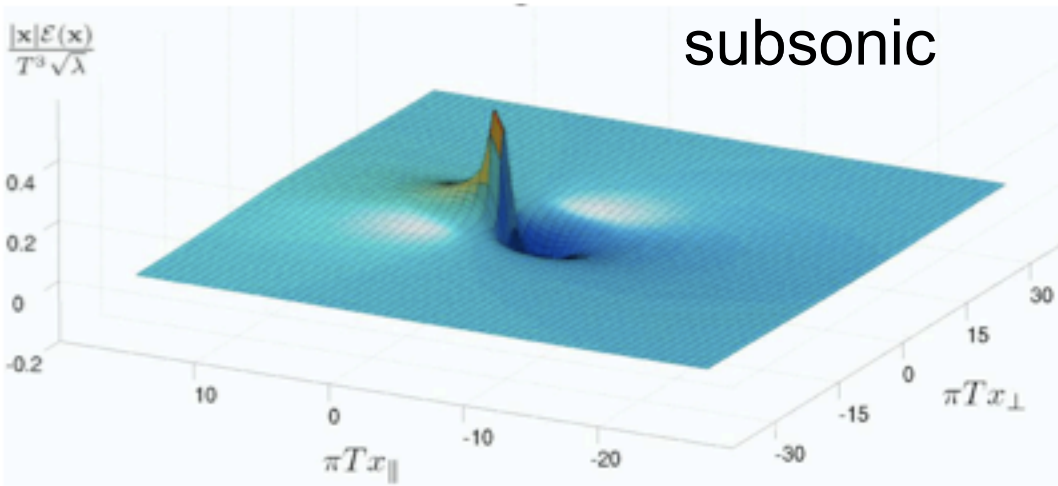
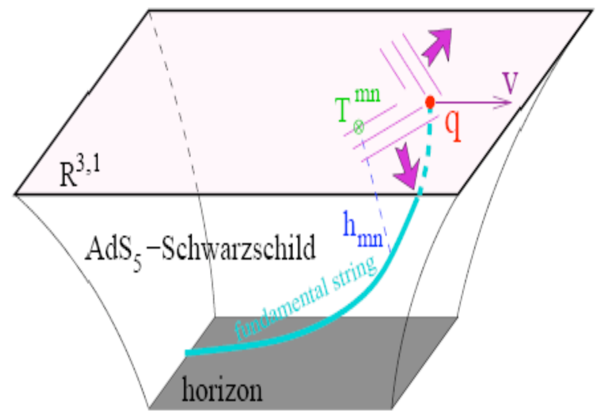



FIG. 1: Plot of $|\mathbf{x}|\,\mathcal{E}(\mathbf{x})/(T^3\sqrt{\lambda})$ for $v = 1/4$, with the zero temperature and near zone (20) contributions removed. Note the absence of structure in the region $|\mathbf{x}| \gg 1/\pi T$.




igure 1: The $AdS_5$-Schwarzschild background is part of the near-extremal D3-brane, which ncodes a thermal state of $\mathcal{N} = 4$ supersymmetric gauge theory [25]. The external quark rails a string into the five-dimensional bulk, representing color fields sourced by the quark's undamental charge and interacting with the thermal medium.

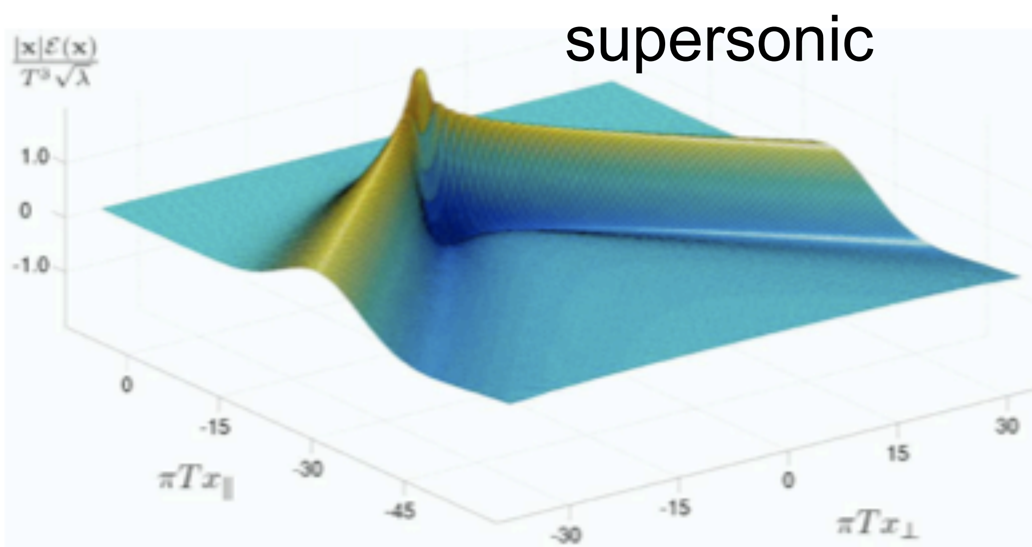



FIG. 2: Plot of $|\mathbf{x}|\,\mathcal{E}(\mathbf{x})/(T^3\sqrt{\lambda})$ for $v = 3/4$, with the $T$=0 and near zone (20) contributions removed. A Mach cone is clearly visible, with an opening half-angle $\theta \approx 50°$.

**Left: P.Chesler,L.Yaffe**
**Up- from Gubser et al**

**Both groups made Amasingly detailed Description of the conical flow from AdS/CFT=> not much is diffused**

# Entropy production

## estimates of area of trapped surface

A significant leap forward had been done recently by Gubser, Pufu and Yarom [123], who proposed to look at heavy ion collision as a process of head-on collision of two point-like black holes, separated from the boundary by some depth $L$ – tuned to the nuclear size of Au to be about 4 fm, see Fig.??. By using global AdS coordinates, these authors argued that (apart of obvious axial O(2) symmetry) this case has higher – namely O(3)– symmetry with the resulting black hole at the collision moment at its center, thus in certain coordinate

$$q = \frac{\vec{x}_\perp^2 + (z-L)^2}{4zL} \tag{91}$$

the 3-d trapped surface C at the collision moment should be just a 3-sphere, at constant $q = q_c$. (Here $x_\perp$ are two coordinates transverse to the collision axes.) The picture of it is shown in Fig.29(b)

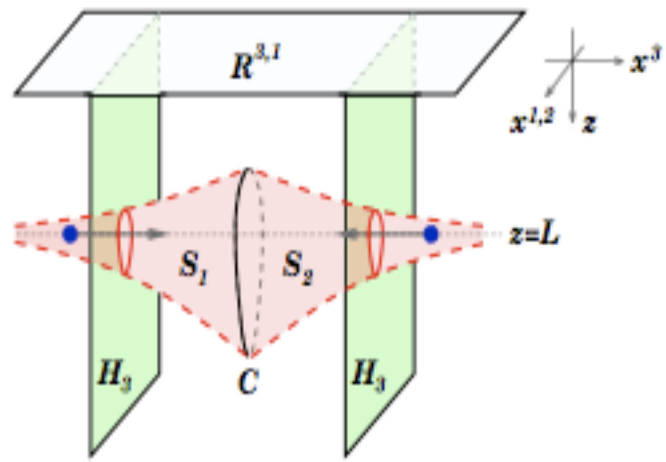
If so, one can find the radius at which it is the trapped null-surface and determine its energy and Bekenstein entropy. For large $q_c$ these expressions are

$$E \approx \frac{4L^2 q_c^3}{G_5}, \quad S \approx \frac{4\pi L^3 q_c^2}{G_5}, \tag{92}$$

from which, eliminating $q_c$, the main result of the paper follows, namely that the entropy grows with the collision energy as

$$S \sim E^{2/3} \tag{93}$$

Note that this power very much depends on the 5-dimentional gravity and is different from the 1950's prediction of Fermi and Landau (??) in which this power was 1/2 and (accidentally or not) fits the data better.




- Gubser,Pufu and Yarom" Heavy ion collisions as that of two black holes

# Grazing Collisions of Gravitational Shock Waves and Entropy Production in Heavy Ion Collision

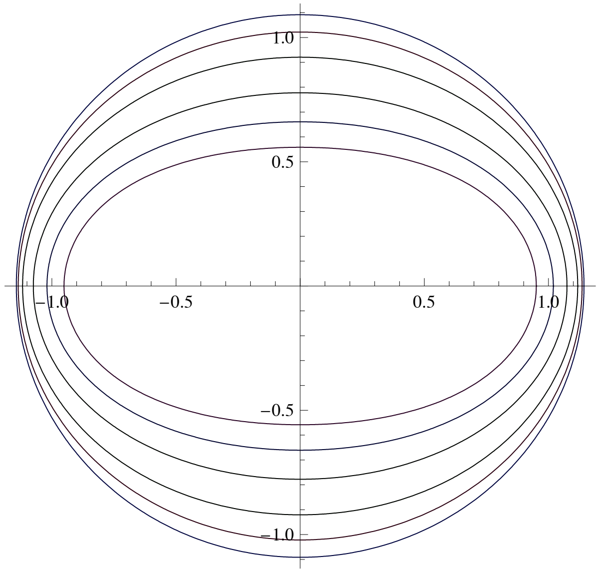
Shu Lin[1], and Edward Shuryak[2]

The shock wave moving in $+x^3$ direction is given by:

$$ds^2 = L^2 \frac{-dudv + (dx^1)^2 + (dx^2)^2 + dz^2}{z^2} + L \frac{\Phi(x^1, x^2, z)}{z} \delta(u) du^2$$

with $\Phi(x^1, x^2, z)$ satisfies the following equation:

$$\left(\Box - \frac{3}{L^2}\right) \Phi = 16\pi G_5 J_{uu}$$




The vanishing of expansion gives the equation:

$$\left(\Box - \frac{3}{L^2}\right) (\Psi_1 - \Phi_1) = 0$$

$$\Psi_1|_{\mathcal{C}} = \Psi_2|_{\mathcal{C}} = 0$$

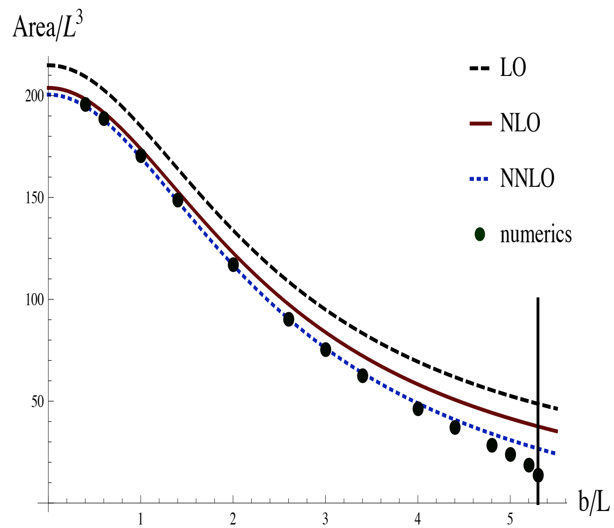
The boundary $\mathcal{C}$ should be chosen to satisfy the constraint:

$$\nabla\Psi_1 \cdot \nabla\Psi_2|_{\mathcal{C}} = 4$$

# Off-center collisions in AdS$_5$ with applications to multiplicity estimates in heavy-ion collisions

Steven S. Gubser,* Silviu S. Pufu,† and Amos Yarom‡

Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544, USA



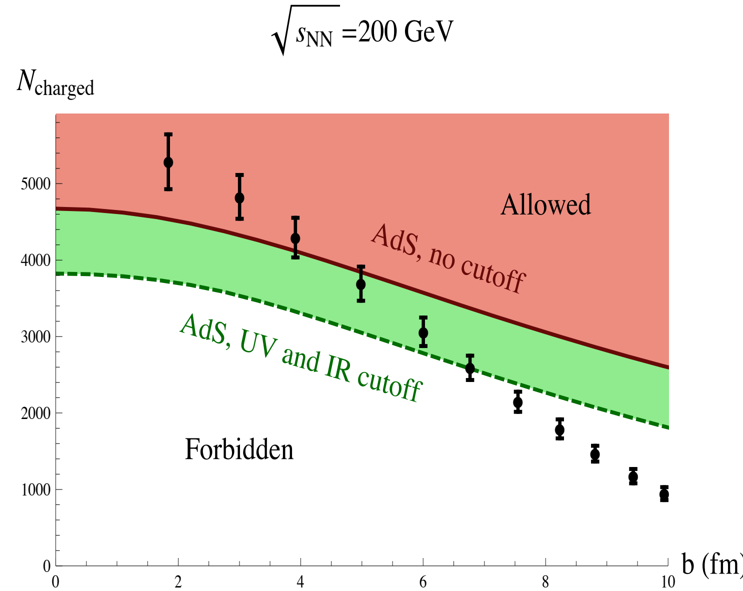
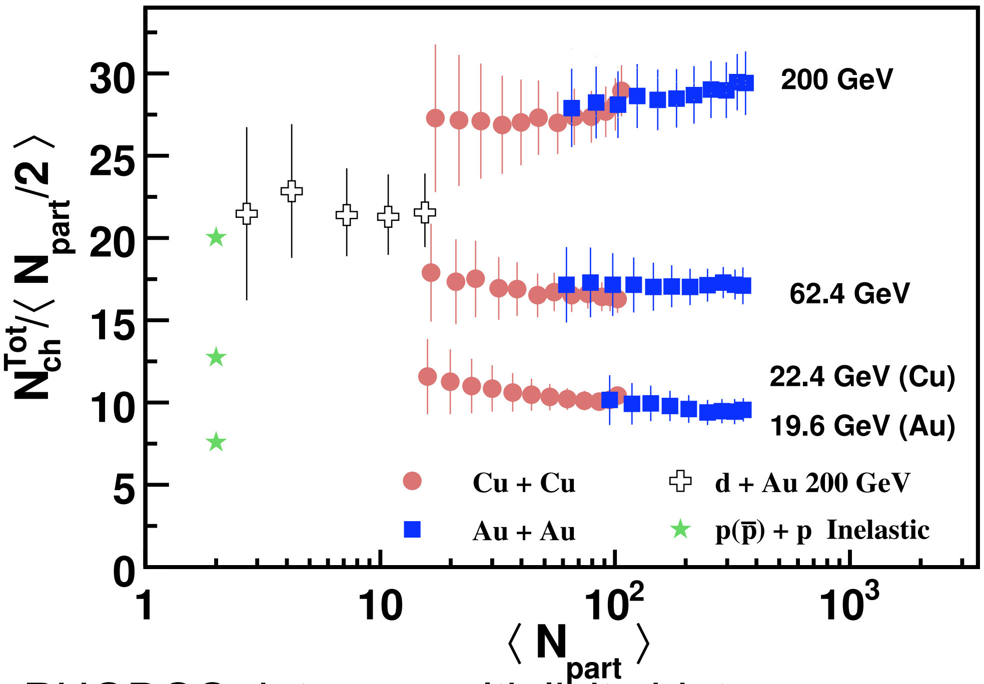



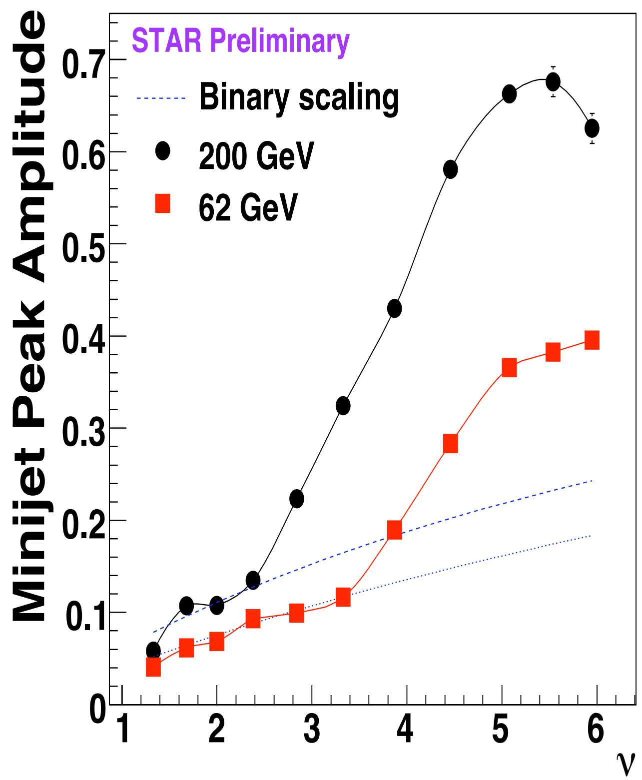

Figure 1: (Color online.) Comparisons between the numerics of [36] and the analytic formula (58). The black dashed curve represents the leading term in (58); the solid red curve corresponds to the first two terms in (58); the dotted blue curve represents the expression (58), which is correct up to a term of order $\mathcal{O}(1/\zeta^2)$; the green dots represent the numerical evaluations used in figure 3 of [36]; lastly, the vertical green line marks the place where, according to [36], the maximum impact parameter $b_{\rm max}/L$ occurs. We thank S. Lin and E. Shuryak for providing us with the results of their numerical evaluations.

# Grazing collisions have no black hole: it disappears with a **finite jump**!

## **Do we see something similar in experiment?**




PHOBOS data on multiplicity hint for a jump but do not really show it




STAR data about ``ridge”

# Summary of part 3

- AdS/CFT => strong coupling => no jets
- It is especially good tool to study strongly coupled conformal plasmas
- Gravitational collisions =>black hole formation => jumps for non-central collisions => perhaps jump in pp s-dependence
- ``pomeron" transition from weak to strong coupling very nontrivial