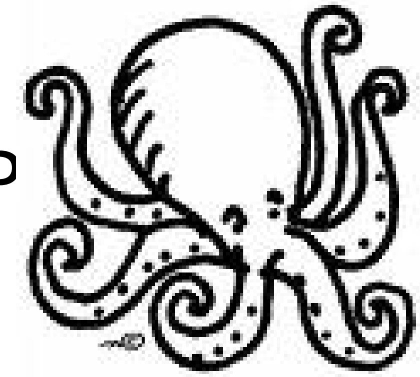
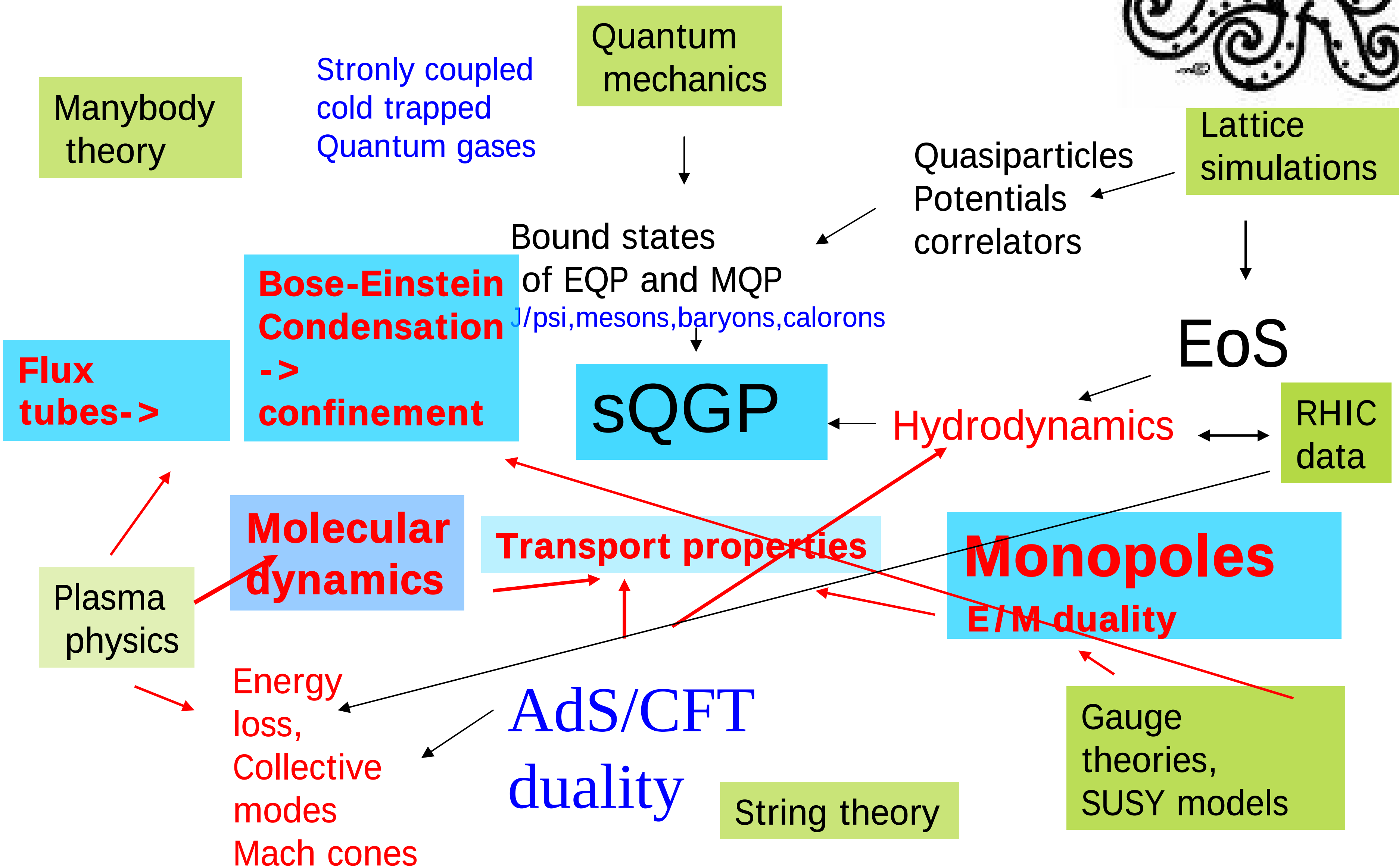
Understanding equilibration in strongly coupled quark-gluon plasma (sQGP)

(KITP program
Santa Barbara,Jan.2008)

Edward Shuryak
Stony Brook

The emerging theory of sQGP





- Part I (in equilibrium)
- RHIC findings: collective flows and jet quenching

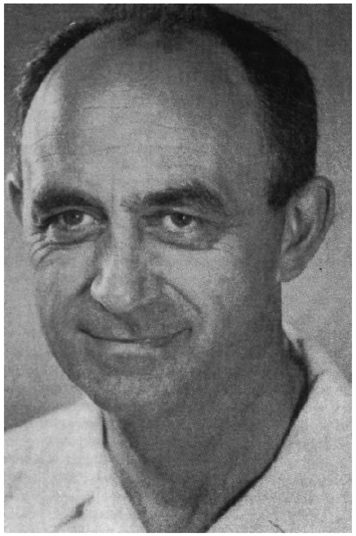
Why is quark-gluon plasma (sQGP) at RHIC such a good liquid? Is it related to deconfinement?
What is the role of e/m duality and magnetic objects in sQGP?

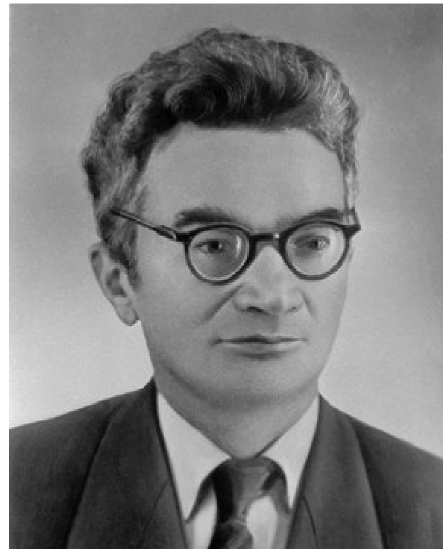
- Electric and magnetic quasiparticles (EQPs and MQPs) are fighting for dominance (J.F.Liao,ES, hep-ph/0611131,PRC 07) The trapping via magnetic bottle effect qualitatively explains results of molecular dynamics (MD) of Non-Abelian plasma with monopoles(B.Gelman, I.Zahed,ES, PRC74,044908,044909 (2006), J.F.Liao,ES, hep-ph/0611131,PRC 07):
- transport summary; RHIC vs both dualities - AdS/CFT and sQGP with monopoles
- - seem to work. Are they related??? LHC will tell
- Few aps of AdS/CFT in equilibrium, T

Part II: equilibraiton in AdS/CFT

- =>Objects falling into black hole
- Colliding heavy quarks: AdS/CFT “Lund model”
- Scaling and nonscaling open string solutions
- **Hologramm** of a falling string as seen on the boundary, **nonthermal explosion**
- Many strings: beyond probe approximation: **2 dynamical membranes** -- matter and horizon ones -- produce entropy
- Instead of summary - **list of homework problems**

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: (predicted <n> scales as $s^{1/4}$)
- Pomeranchuck (1952): interaction strong till freezeout
- Landau (1953): used 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 in 1950's yet, but Landau pole}

My hydro before RHIC

- Hydro for e+e- as a spherical explosion PLB 34 (1971) 509

=> killed by as.freedom (1973) and (1976) discovery of jets in e+e- at SLAC

- Looking for it in pp: radial flow at ISR? ES+Zhirov, PLB (1979) 253:

=>Killed by apparent absence of transverse flow in pp

⇒ ES+Hung, 1996 (PRC57 1891), radial flow at PbPb at CERN SPS with correct freezeout surface **worked!**

⇒ **So we made predictions for RHIC based on that…**

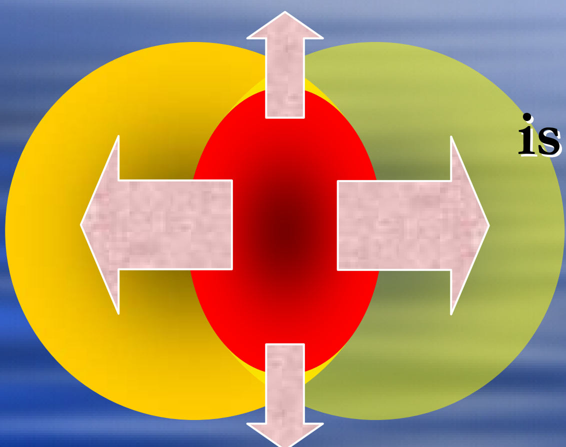
RHIC findings (2000-2007)

- Strong radial and elliptic flows are very well described by **ideal hydro** => small eta/s =>``the most perfect liquid known"
- Strong **jet quenching**, well beyond pQCD gluon radiation rate, same for heavy charm quarks (b quark data coming…)
- Jets destroyed and their energy goes into hydrodynamical **``conical flow"**

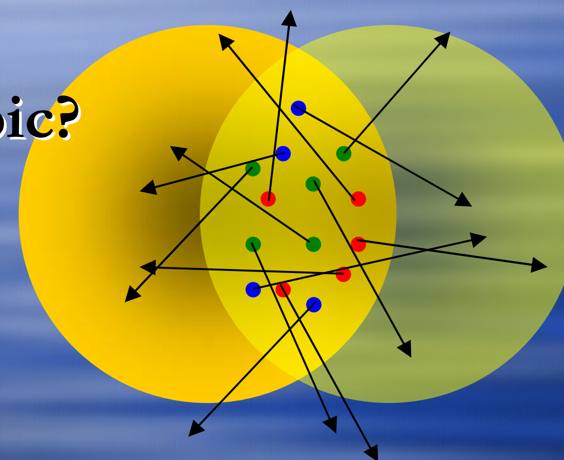
Contrary to expectations of most, hydrodynamics does work at RHIC!

Elliptic flow

How does the system respond to initial spatial anisotropy?



is it macro or microscopic?



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

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

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

Paul Romatschke[1] and Ulrike Romatschke[2]

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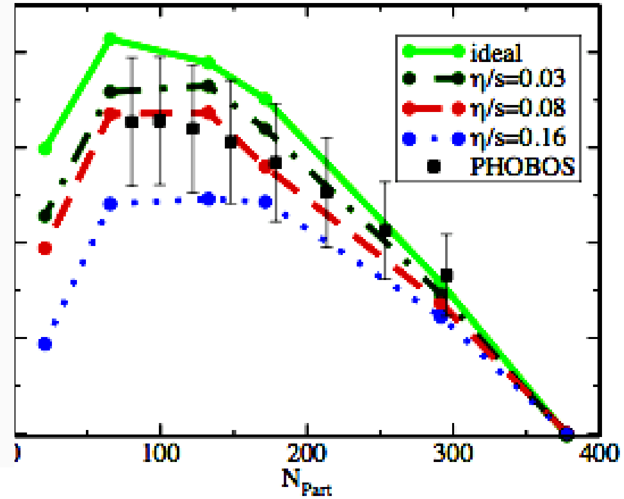
(Dated: October 26, 2007)

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.



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

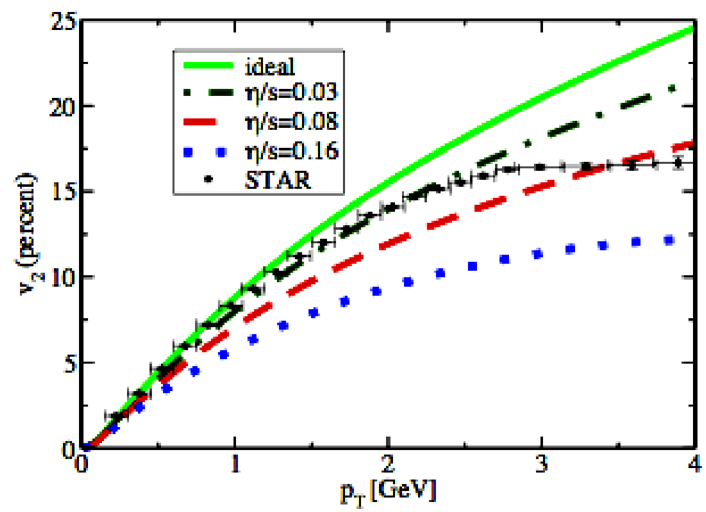


FIG. 3: PHOBOS [24] data on p_T integrated v_2 and STAR [25] data on minimum bias v_2, for charged particles in Au+Au collisions at $\sqrt{s} = 200$ GeV, compared to our hydrodynamic model for various viscosity ratios η/s. Error bars for PHOBOS data show 90% confidence level systematic errors while for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

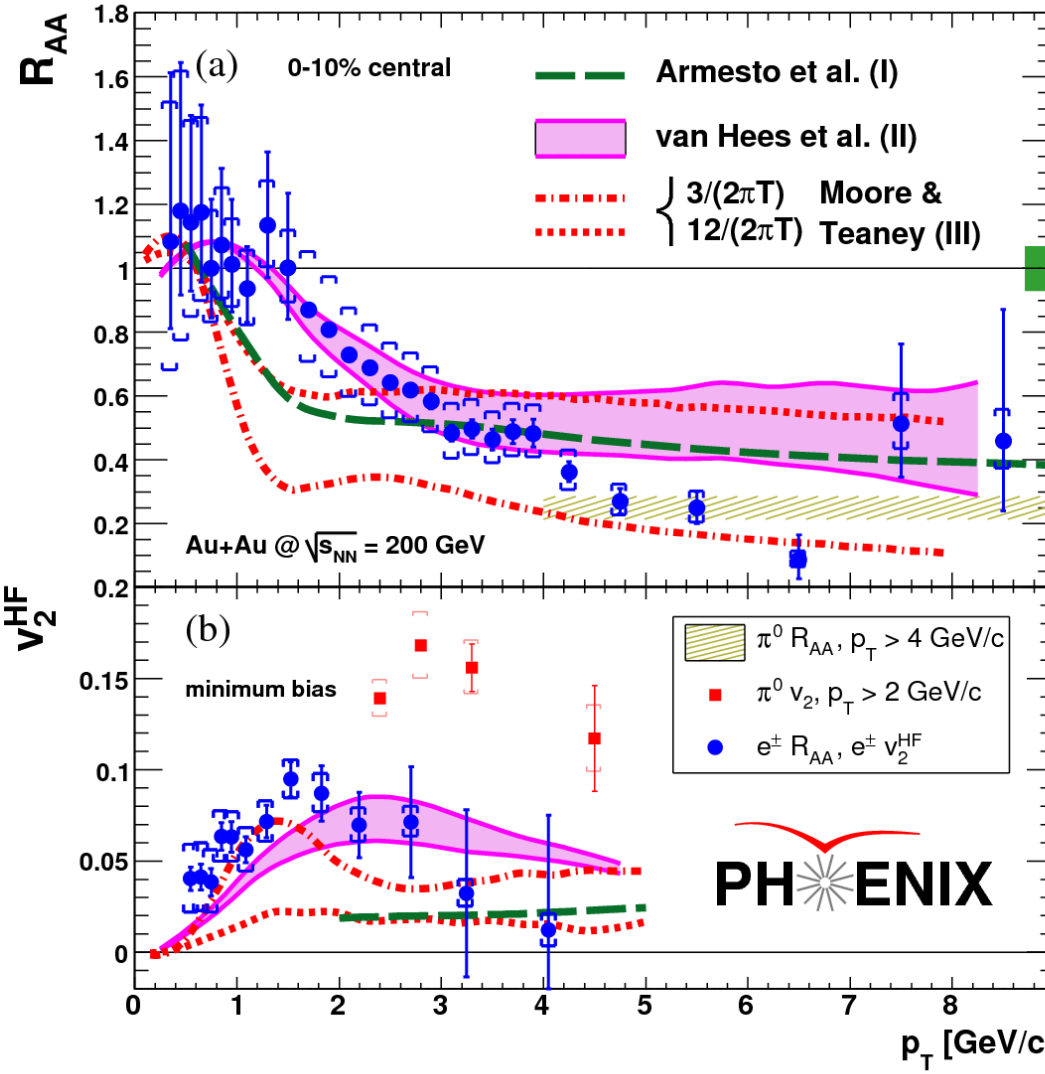
One more surprise from RHIC: strong jet quenching and flow of heavy quarks

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 τ or diffusion coefficient D_{HQ} inferred for charm.

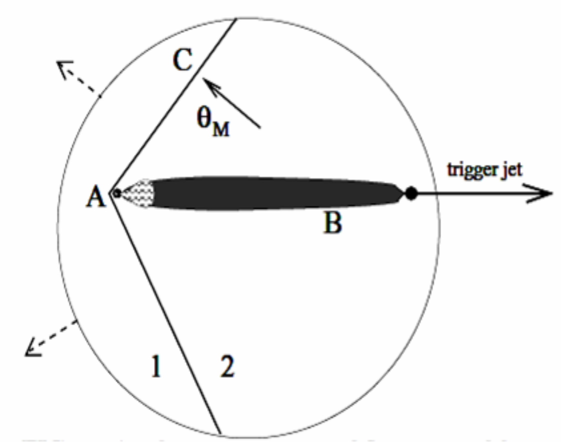


Sonic boom from quenched jets

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**
- **If there are start and end points, there are two spheres and a cone tangent to both**

Wake effect or "sonic boom"

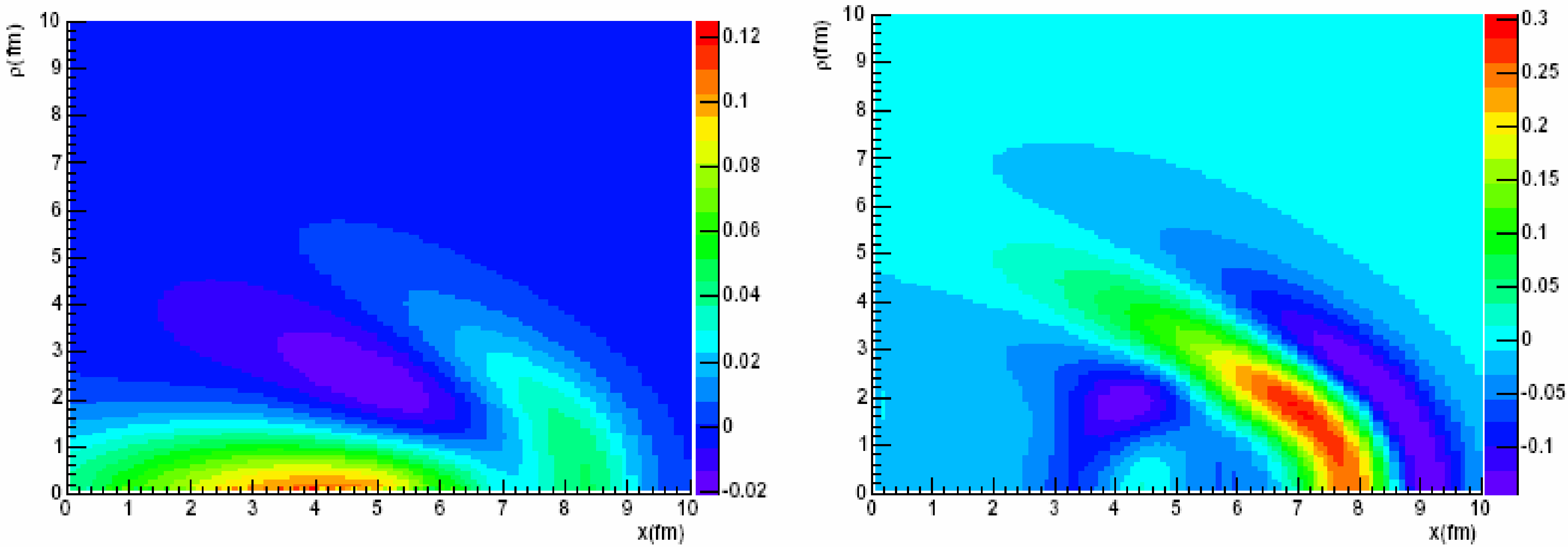


Two hydro modes can be excited

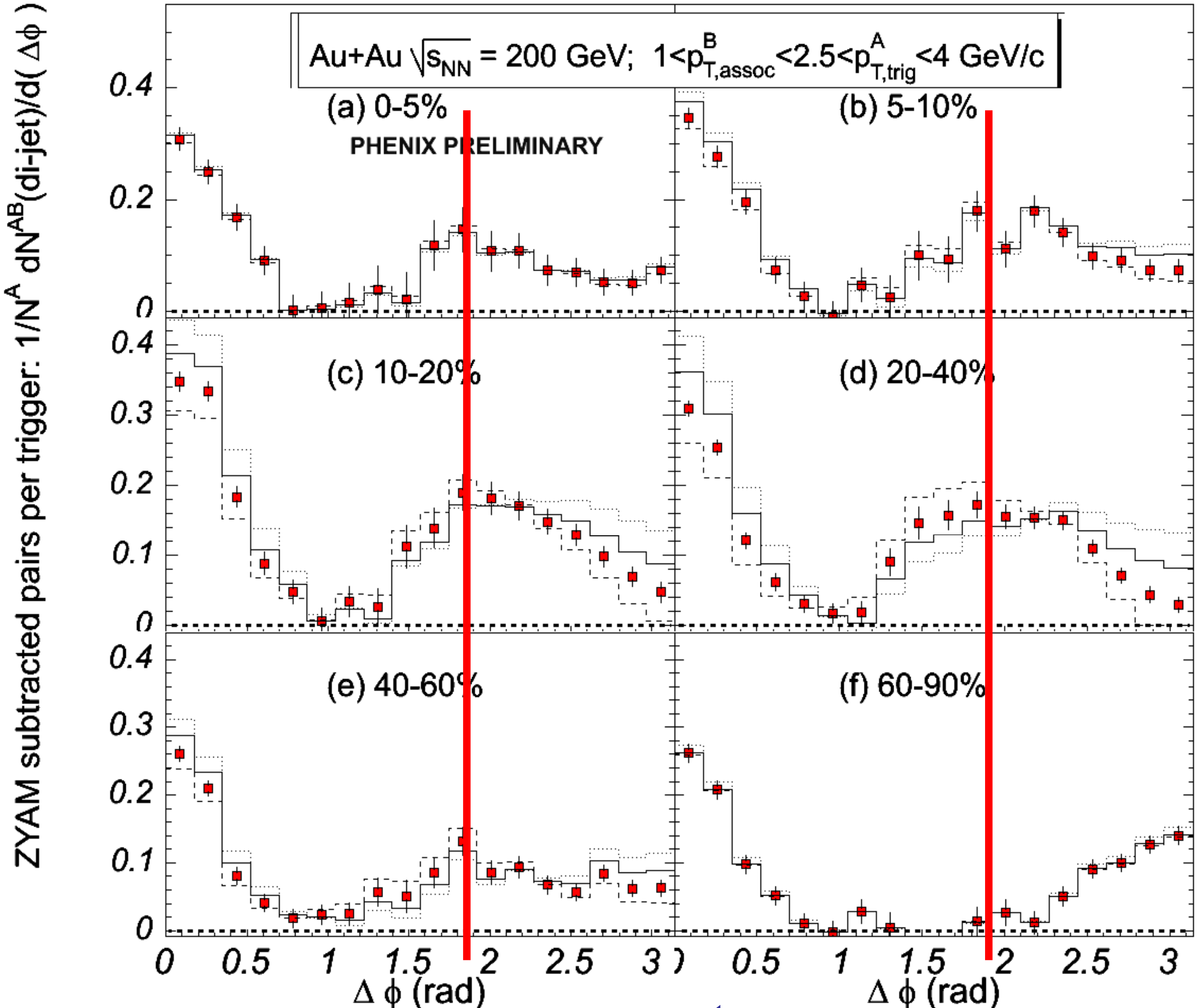
(from our linearized hydro solution):

$$\epsilon_{dt_0}(t=t0,\vec{x}) = e_0(z,r) \quad , \quad \vec{g}_{dt_0}(t=t0,\vec{x}) = g_0(z,r)\delta^{ix} + \vec{\partial} g_1(z,r) \; .$$

a ``diffuson” **a sound**



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

Electric/magnetic duality and transport in sQGP

magnetically charged Quasiprticles in sQGP (monopoles and dyons)

⇒Completely new plasmas

⇒Unexpected properties

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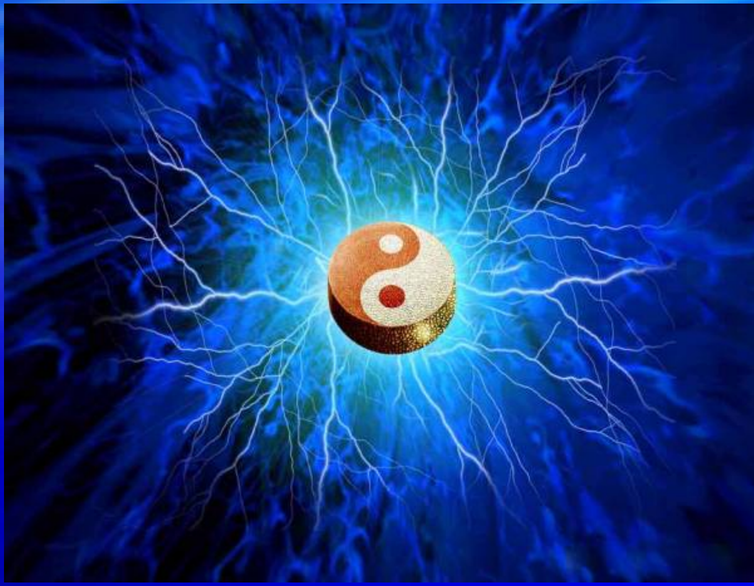


ew Insight: MQPs Are Important in sQGP

- 't Hooft-Mandelstam: QCD Vacuum as Magnetic Superconductor
  - — Condensate of *magnetic D.o.F* occupies vacuum
  - — Original *electric D.o.F* in L_{QCD} gets confined.
  - — Best explored on lattice (Bali; Chernodub;Suzuki; Bornyakov; ...)

- *Bottom-up*: heating up condensate $\longrightarrow$ vaporization $\longrightarrow$ MQPs in plasma

- Lesson from Seiberg-Witten Theory ($N = 2$ SYM)

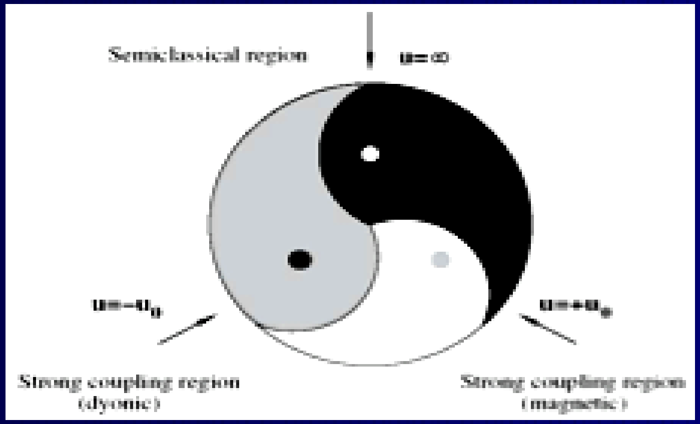


Figure 3: Quantum moduli space of Seiberg-Witten Theory.

- *Top-down*: cooling down to $T_c \longrightarrow$ monopoles become light and weakly-coupled $\longrightarrow$ electric coupling becomes strong.

J.F.Liao,ES,06

New (compactified) phase diagram describing an electric-vs-magnetic competition

Dirac condition **(old QED-type units e^2=alpha, deliberately no Nc yet)**

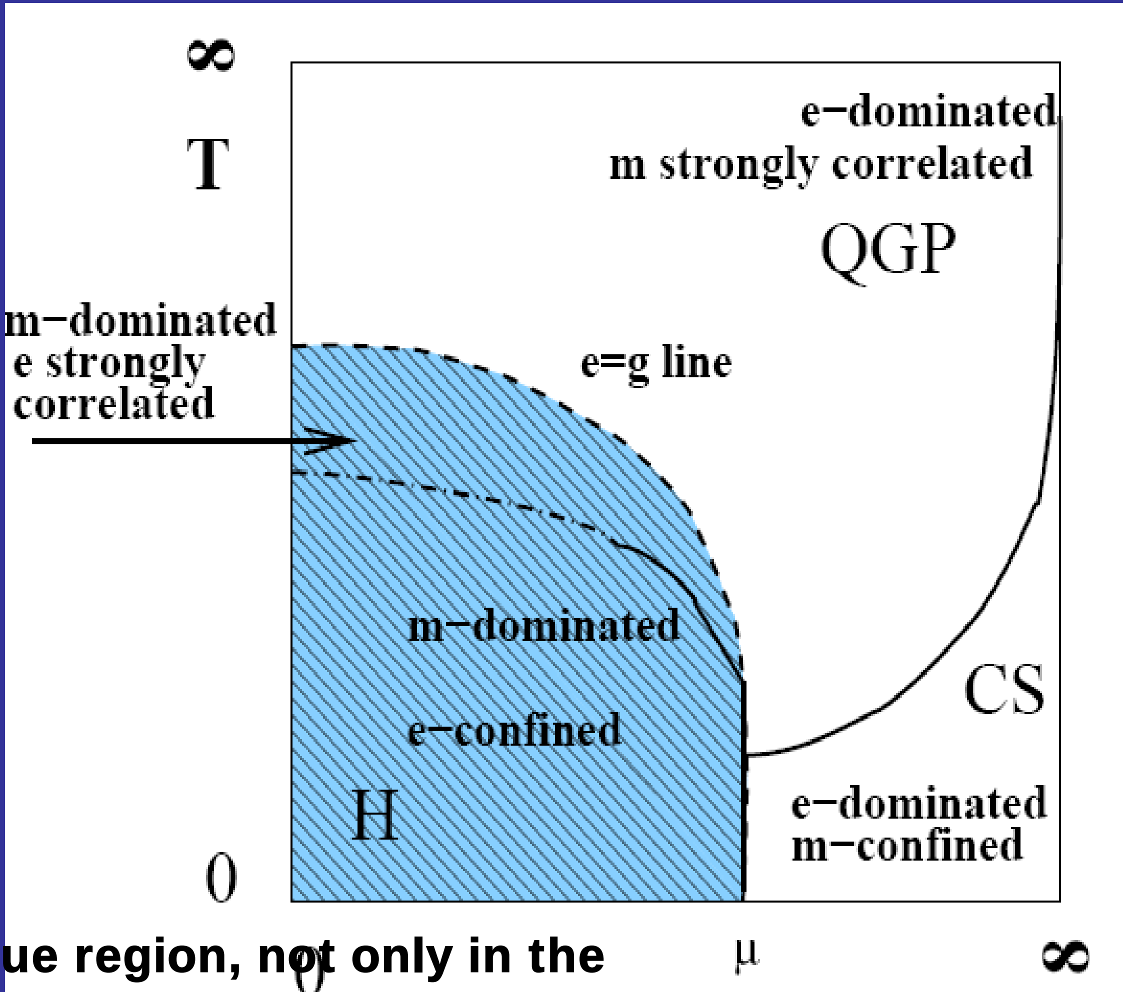
$$\frac{eg}{\hbar c} = \frac{n}{2}$$

Thus at the e=g line

$$e^2/\hbar c = g^2/\hbar c = 1$$

Near deconfinement line
g->0 in IR

$\Rightarrow$e-strong



There are e-flux tubes in all blue region, not only in the confined phase! In fact, they are maximally enhanced at Tc

GEF-TH 22/07

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

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Note that the relative monopole density grows as T=> Tc

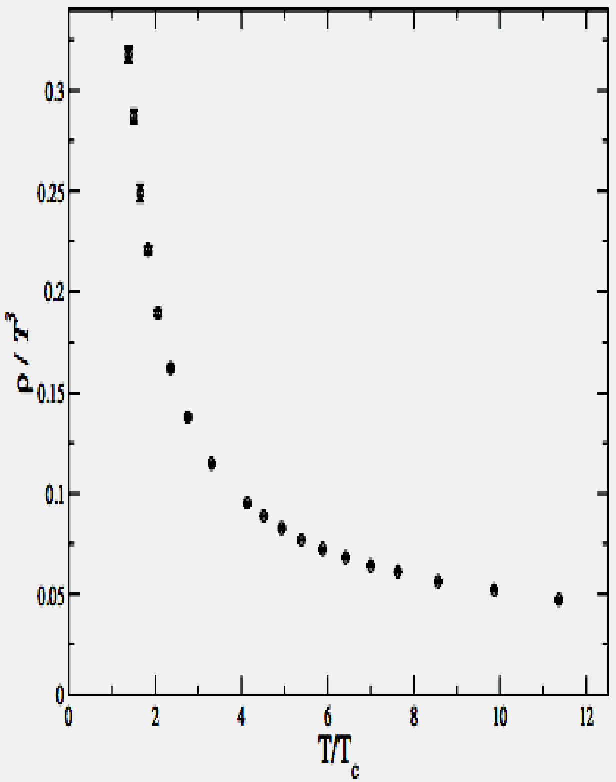


FIG. 3. $\rho(T)/T^3$ as a function of T/T_c. Data have been obtained on a $48^3 \times L_t$ lattice, with variable L_t and at $\beta = 2.75$ (first 9 points), and variable β at $L_t = 4$ (last 10 points).

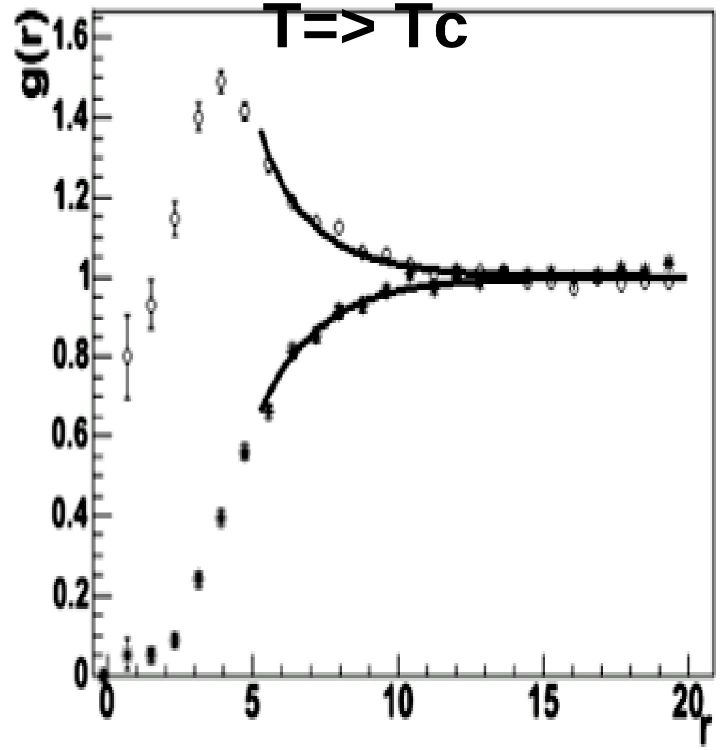


FIG. 5. $g(r)$ for the monopole-monopole (stars) and monopole-antimonopole (circles) case on a $40^3 \times 5$ lattice at $\beta = 2.7$ ($T \simeq 2.85\ T_c$). The reported curves correspond to fits according to $g(r) = \exp(-V(r)/T)$ with $V(r)$ a Yukawa potential (see Eqs. (2.9) and (2.10)).

C.Ratti,ES: monopole masses explain this trend, they get 3-4 times lighter than
Electric ones (q,g). Cristoforetti,ES: mass from Bose condesation condition

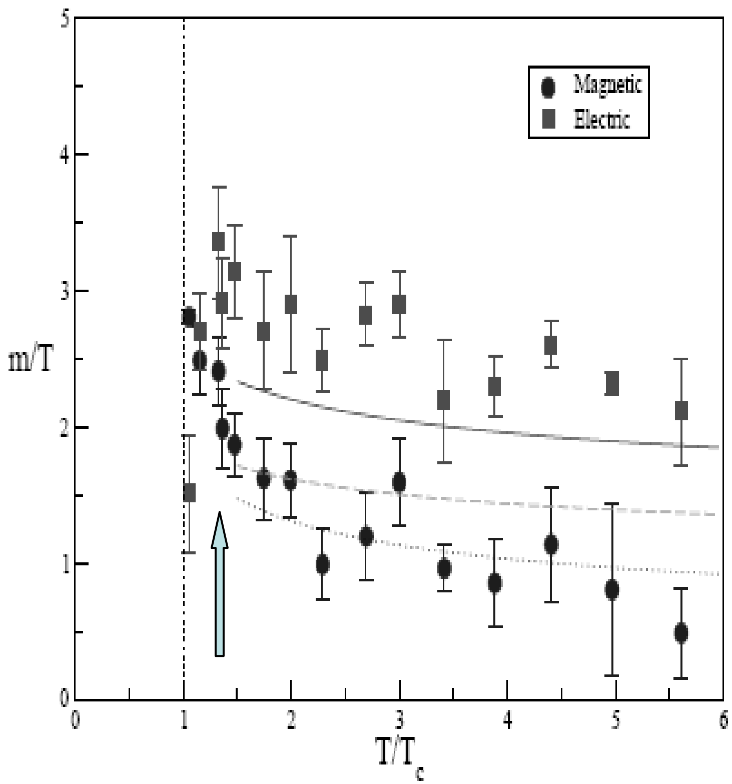
Electric and magnetic scrrening Masses, Nakamura et al, 2004

My 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)

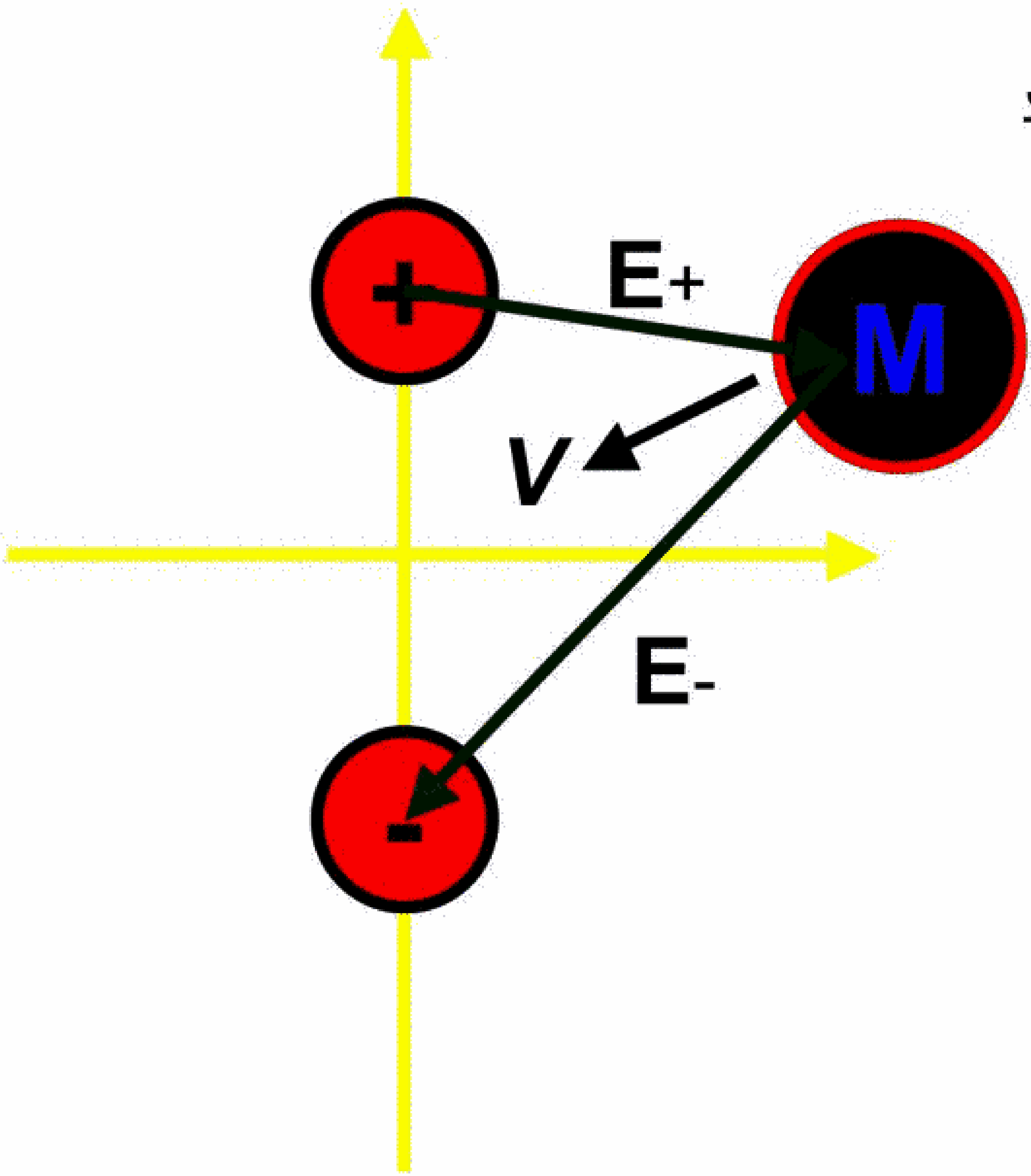
Other data
(Karsch et al)
better show how
Me
Vanishes at Tc



Me>Mm
Electrric
dominated

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

So why is such plasma a good liquid? Because of magnetic-bottle trapping:



static eDipole+MPS

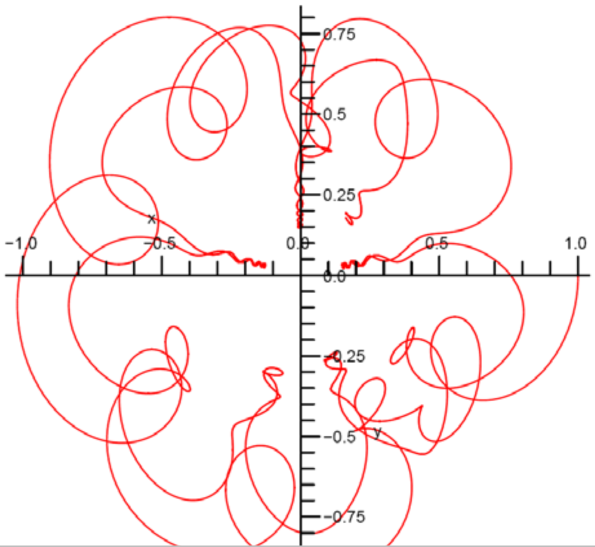
Note that Lorentz force is O(v)!

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

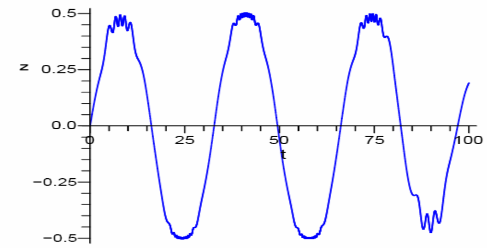
$$\vec{E} = e\,[\frac{\vec{r}-a\vec{z}}{|\vec{r}-a\vec{z}|^3} - \frac{\vec{r}+a\vec{z}}{|\vec{r}+a\vec{z}|^3}]$$

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

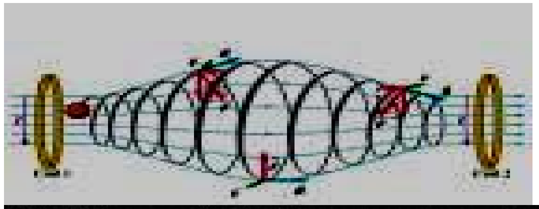
We found that **two charges** play ping-pong by a monopole without even moving!

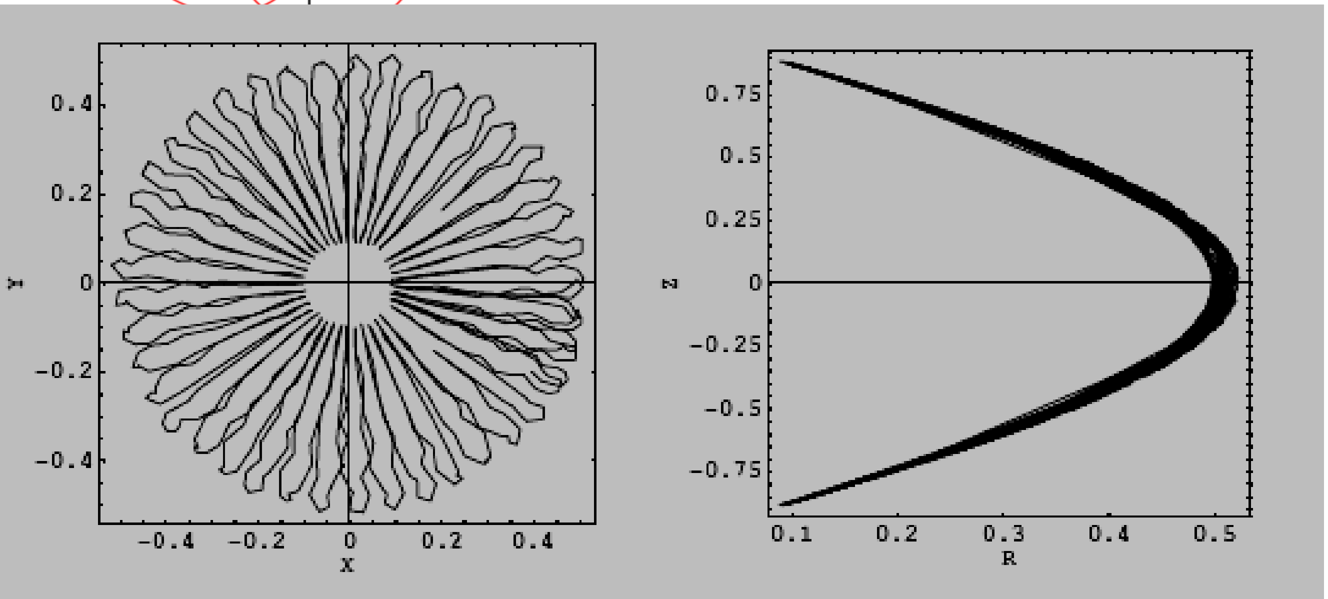


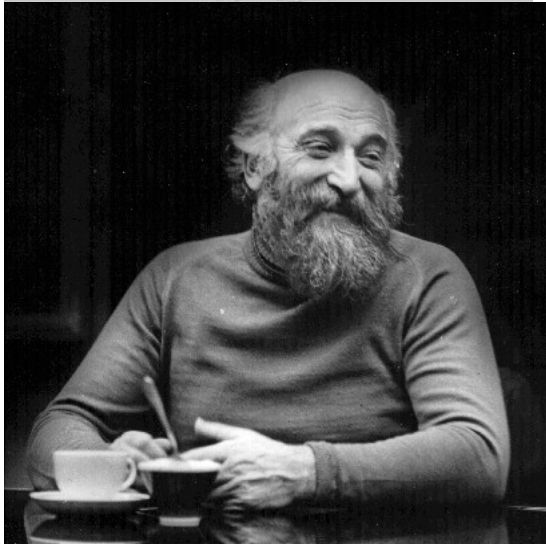
Chaotic, regular and escape trajectories for a monopole, all different in initial condition by 1/1000 only!



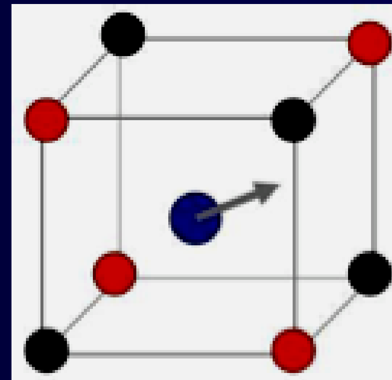
Dual to Budker's magnetic bottle





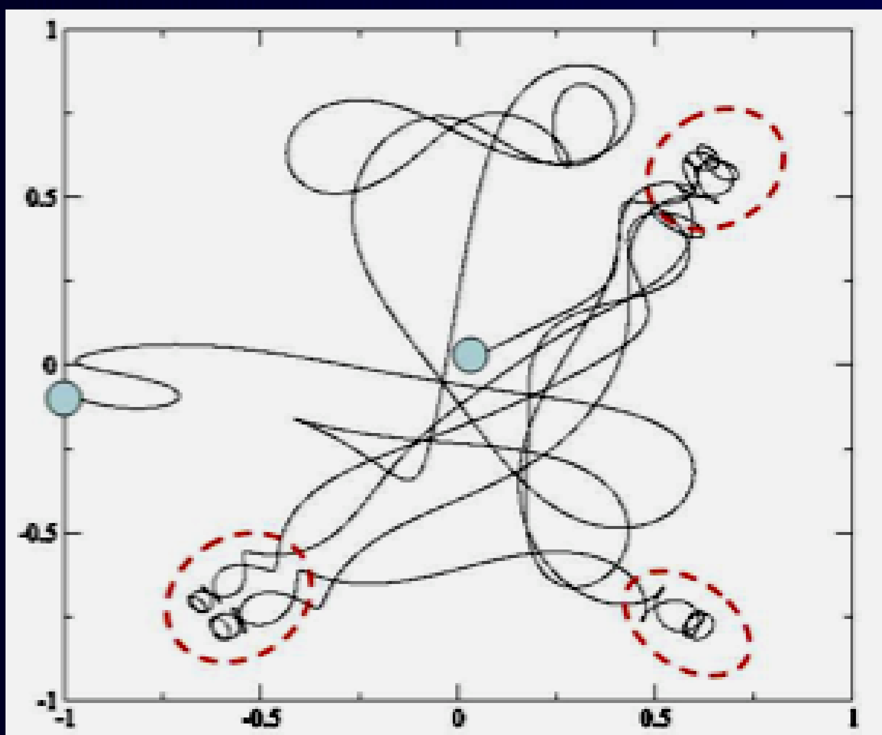


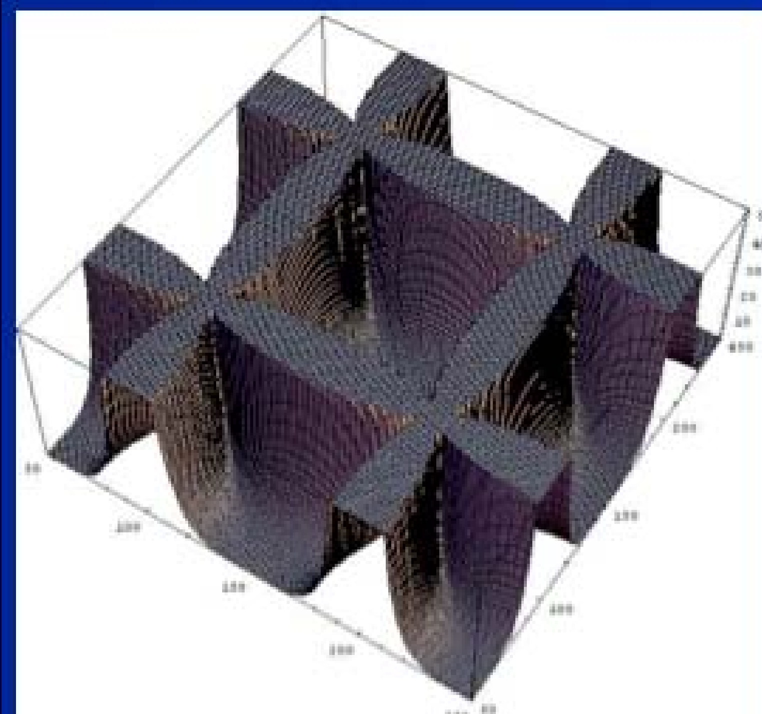
- MQP in the field of a cube with alternating charges at corners.



Another example: a monopole in a “grain of solt”
Liao and ES, in progress
escape time Gamma^(.5-.6)

ge”





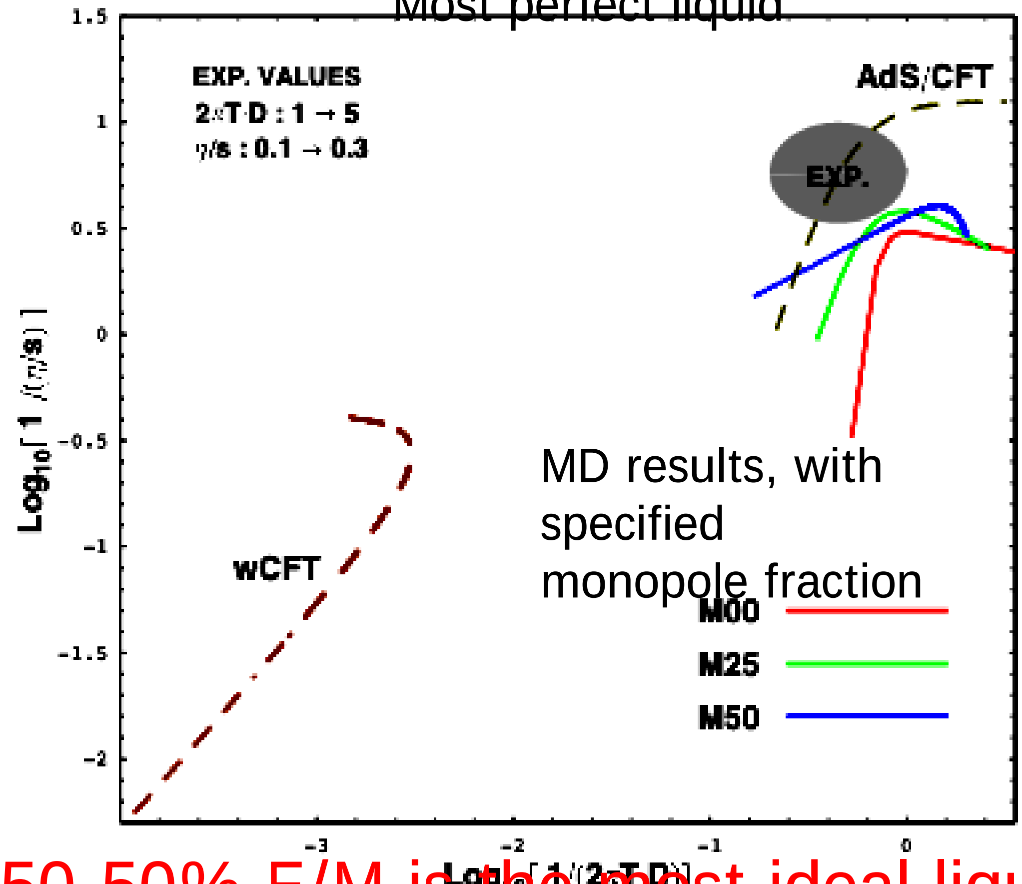
short transport summary

log(inverse viscosity s/eta)- vs. log(inverse heavy q diffusion const D*2piT) (avoids messy discussion of couplings)

->Stronger coupled ->

- RHIC data: very small viscosity and diffusion
- **vs theory - AdS/CFT and our MD**

Weak coupling end =>
(Perturbative results shown here)
Both related to mean free path



50-50% E/M is the most ideal liquid

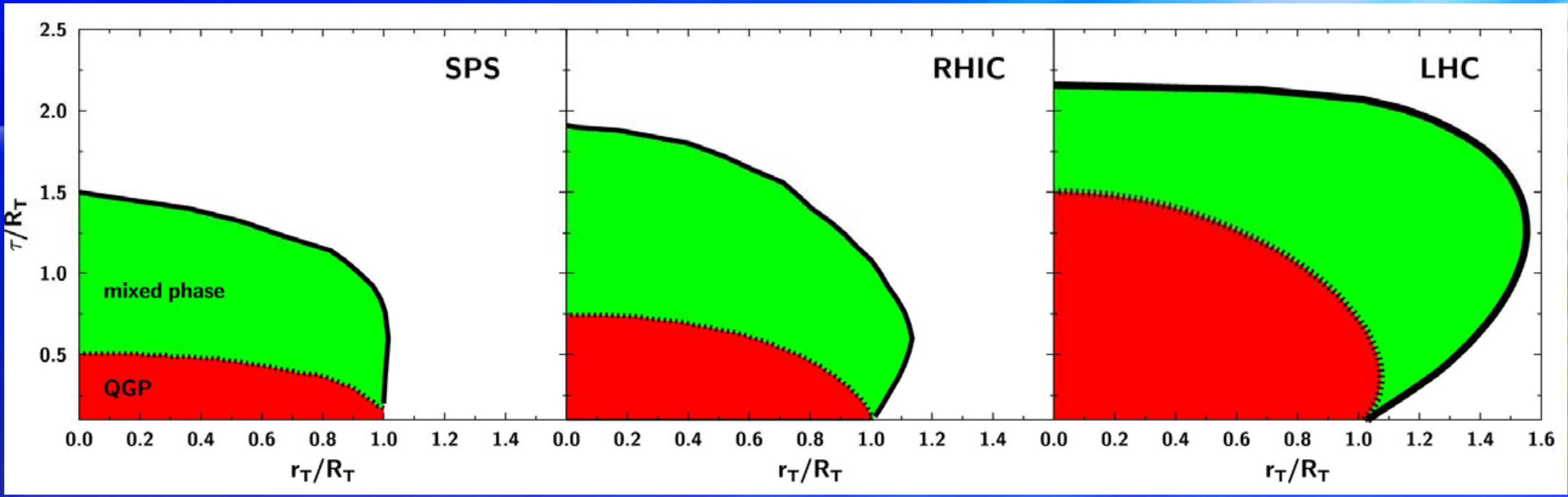
From RHIC to LHC:

(no answers, only 1bn$ questions)

(I don’t mean the price of LHC but ALICE and the rest of heavy ion program)

- Will ``perfect liquid” be still there?
- Is jet quenching as strong, especially for c,b quark jets and much larger pt?
- Is matter response (conical flow at Mach angle) similar?
  (This is most sensitive to viscosity…)

From SPS to LHC

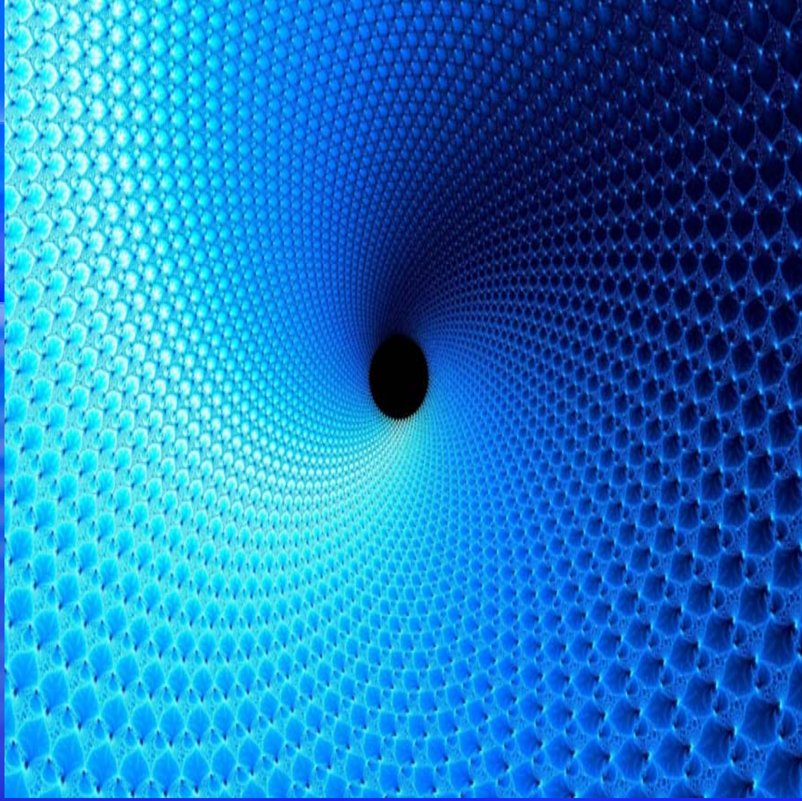


- lifetime of QGP phase nearly doubles, but v2 grows only a little, to a universal value corresponding to EoS p=(1/3)epsilon
- radial flow grows by about 20% => less mixed / hadronic phase (only 33% increase in collision numbers of hadronic phase in spite of larger multiplicity)

(hydro above from S.Bass)

AdS/CFT duality

from gravity in AdS_5 to strongly coupled CFT (N=4 SYM) plasma

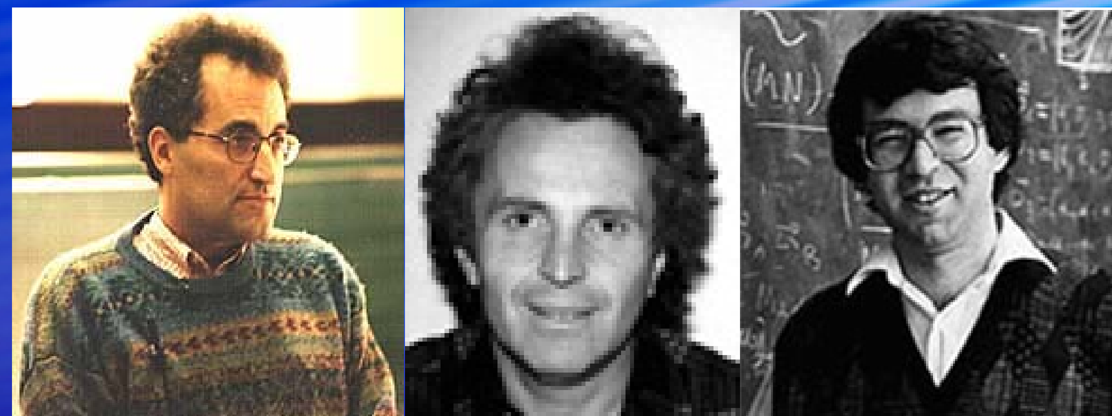


what LHC people dream about
-- a black hole formation --

does happen, in each and every RHIC AuAu event !

What we see at RHIC is a hologramm of this process…

The first gauge-string duality found in 1997



- AdS/CFT correpondence known as ``Maldacena duality”
- Along the long path illuminated by Witten,Polyakov,Klebanov…

The duality setting

- CFT (conformal gauge theory) N=4 SYM a cousin of QCD (chromodynamics=theory of strong interaction) in which the coupling $\lambda = g^2 N_c$ does not run.
- It lives on flat 4-dim boundary of 5-d curved AdS (anti-de-Sitter) space where (super)gravity is a description of (super) string theory
- Correspondence dictionary: everything in the "bulk" reflects on the boundary
- Hint; think of extra dimension as a complex variable trick: instead of functions on the real axes one may think of poles in a complex plane …

The 5th coordinate

- z is the 5th coordinate, dim=length=1/momentum
- its physical meaning is ``scale” as in renorm.group
- **z=>0 is ``high scale” UV** or very high energies, **z=>infinity is low scale or IR**
- $ds^2 = (-dt^2 + dx_1^2 + dx_2^2 + dx_3^2 + dz^2)/z^2$ so distances in z are logarithmic. Light speed is still 1 in all directions
- $z = L^2/r$ where r is distance from b.h. =>

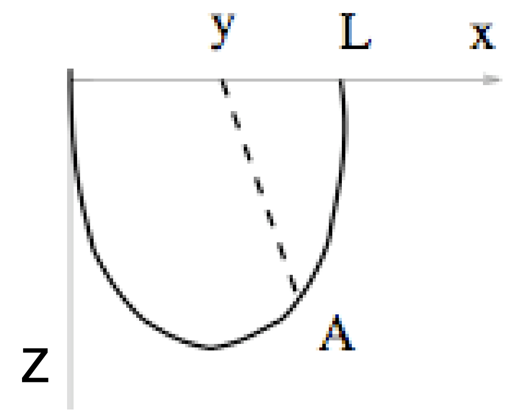
Gravity force is acting toward large z, “stones” fall there

- (unless they are BPS states which levitate --Newton cancels Coulomb)

Maldacena's dipole

strongl coupled Coulomb law

- Maldacena,Rey,Yee -98 one of the first apps:
- The pending string (=flux tube) has minimal action
- Modified Coulomb law at strong coupling, sqrt of the coupling << coupling
- Can it be just a factor, like dielectric constant?



$$E = -\frac{4\pi^2 \left(g_{YM}^2 N\right)^{\frac{1}{2}}}{\Gamma\left(\frac{1}{4}\right)^4 L}$$

A hologramm of a dipole in a stronly coupled vacuum: **not just electric E!**

- Shu Lin,ES arXiv:0707.3135

recently evaluated holographic stress tensor from the Maldacena string

Here is large r behavior:

- $T_{00} \Rightarrow (g^2N)^{1/2}d^3/r^7$

Times function of the Angle which is plotted by a solid line

(to be compared to zero coupling

$\Rightarrow (g^2N)d^2/r^6$

Times another function (dashed)

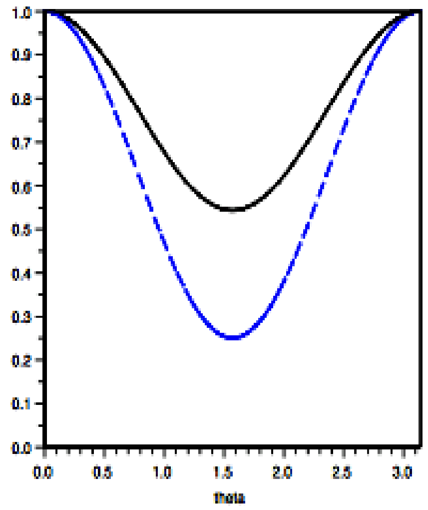


Figure 1: (Color online) The far field energy distribution in polar angle $\theta(cos(\theta) = y_1/|y|)$, normalized at zero angle. Solid (black) line is our result, compared to the perturbative result $(3cos^2 + 1)/4$ given by the dashed (blue) line.

Finite T AdS/CFT (Witten 98)

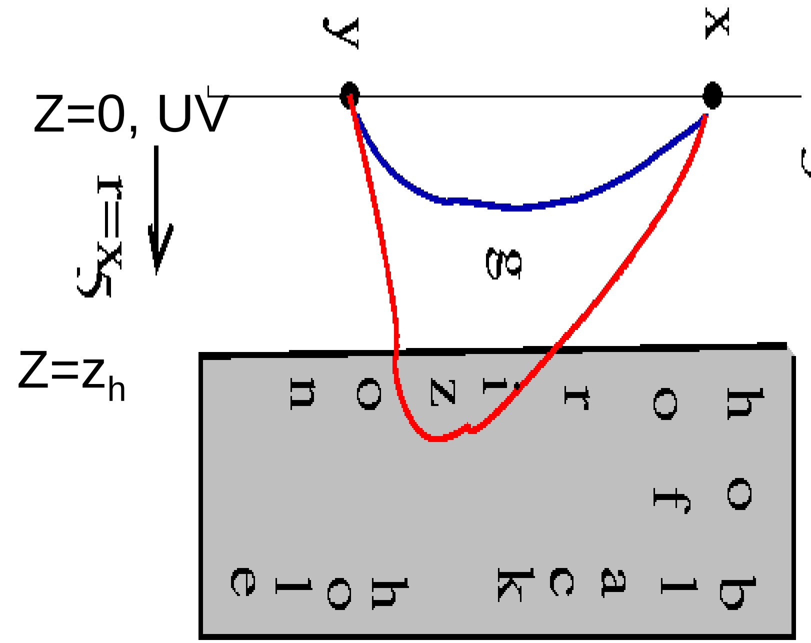
viscosity from Kubo formula $<T_{ij}(x)T_{ij}(y)>$

(Polykastro,Son, Starinets 03)

Horisontal line is our 4d Universe, (x,y are on it)

- Temperature is given by position of a horizon zh of non-extreme BH
- T=T(Hawking)
- **Correlator is just the graviton propagator**
- Blue graviton path does not contribute to Im G, but

red graviton can be lost



The answer is so simple because of boundary condition (universal "black membrane") at the horizon

Sound is a hologram of a wave on the bottom

$$\eta / s = hbar / 4\pi$$

$$\kappa_T = \sqrt{\gamma\lambda} T^3 \pi$$

Heavy quark diffusion

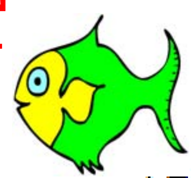
J.Casalderrey+ D.Teaney,hep-ph/0605199,hep-th/0701123

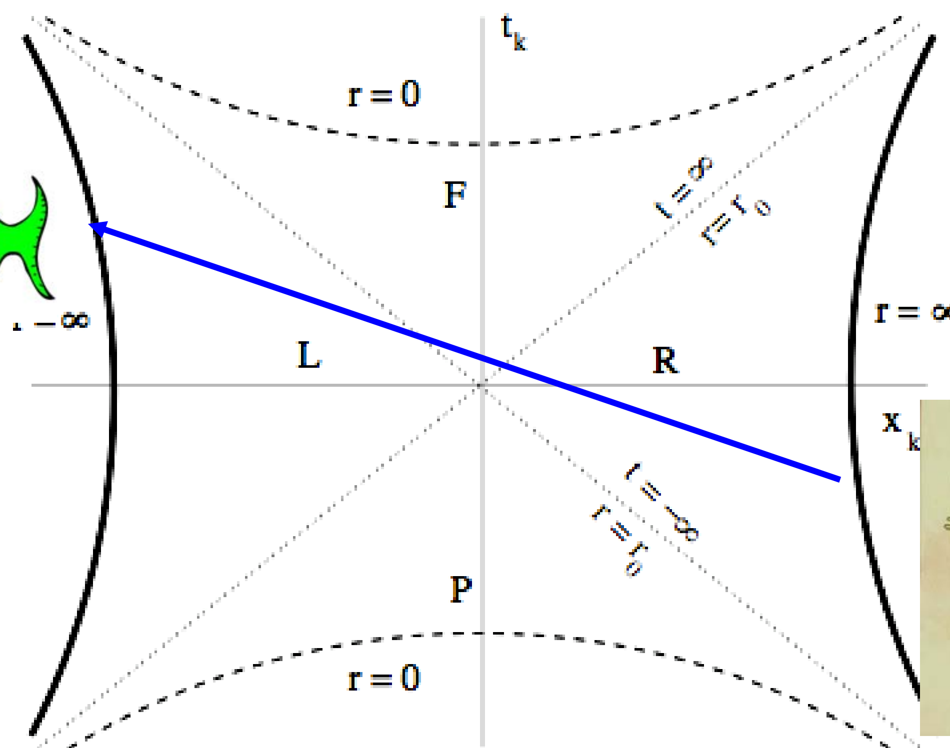
string solution spans the full Kruskal plane and gives access to contour correlations. The diffusion coefficient is $D = 2/\sqrt{\lambda}\pi T$ and is therefore parametrically smaller than momentum diffusion, $\eta/(e+p) = 1/4\pi T$. The quark mass must be much greater than $T\sqrt{\lambda}$ in order to treat the quark as a heavy quasi-particle. The result is discussed in the context of the RHIC experiments.

One quark (fisherman) is In our world, The other (fish) in Antiworld (=conj.amplitude)

String connects them and conduct waves in one direction through the black hole

ANTIWORLD





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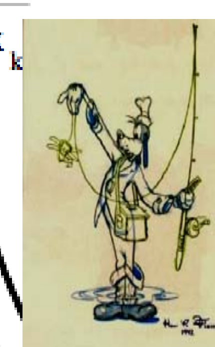


Heavy quark in CFT plasma

has a string deformed by ``hot wind”

Herzog,Yaffe,Gubser…May06
calculated the
drag force = momentum
Flow down the string

Einstein’s relation between drag and diffusion works

But how graviy knows?

$$\eta_D = \frac{T}{M_c D_c}$$

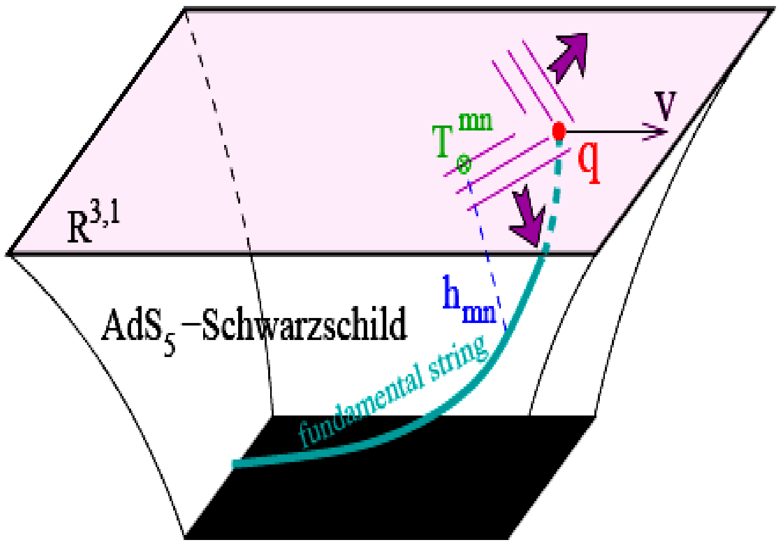


Figure 1: The AdS_5-Schwarzschild background is part of the near-extremal D3-brane, which encodes a thermal state of $\mathcal{N} = 4$ supersymmetric gauge theory [25]. The external quark trails a string into the five-dimensional bulk, representing color fields sourced by the quark's fundamental charge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

subsonic

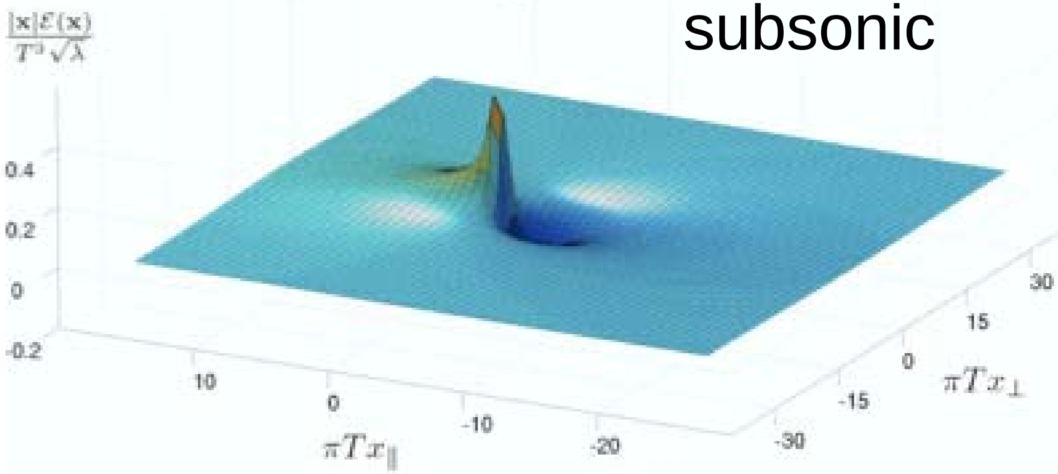


FIG. 1: Plot of $|\mathbf{x}|\,\mathcal{E}(\mathbf{x})/(T^3\sqrt{\lambda})$ for $v = 1/4$, with the zero temperature and near zone (20) contributions removed. Note the absence of structure in the region $|\mathbf{x}| \gg 1/\pi T$.

supersonic

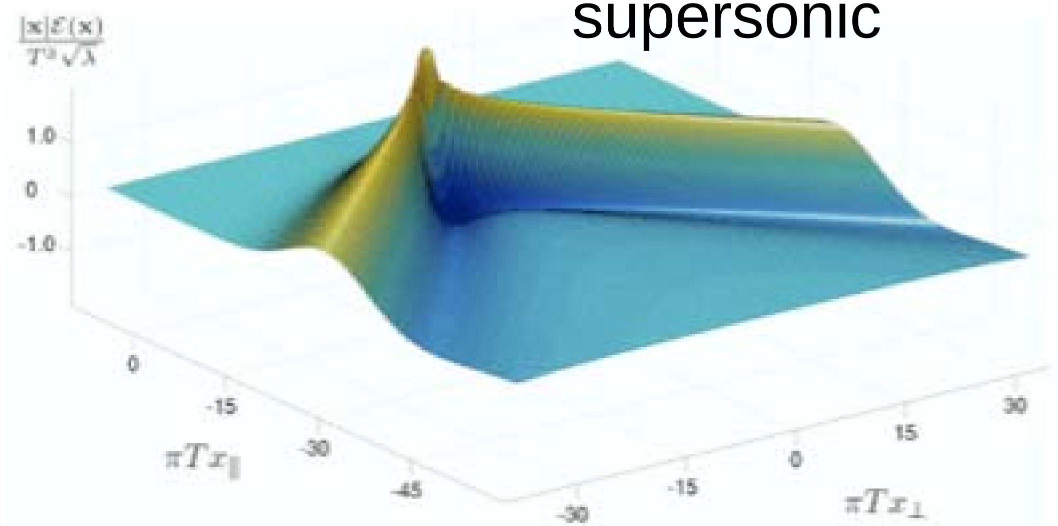


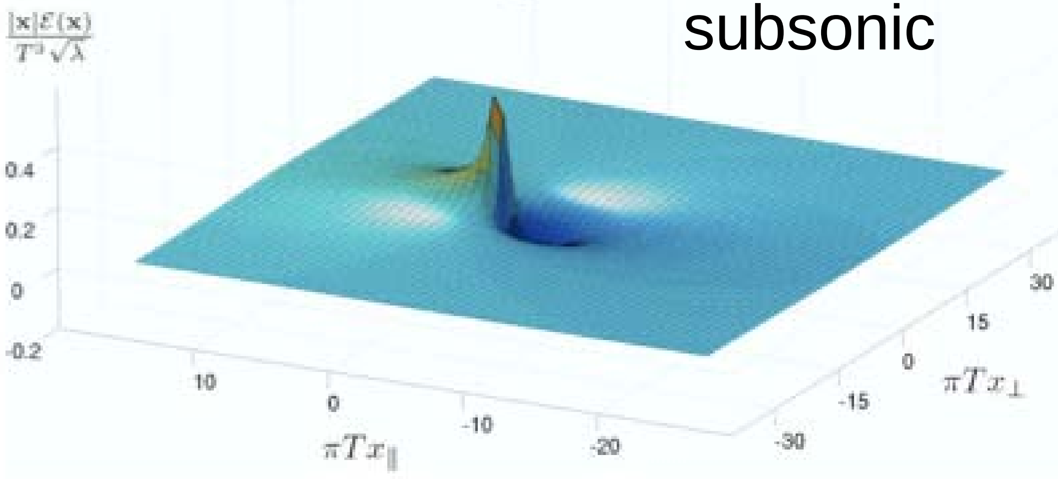
FIG. 2: Plot of $|\mathbf{x}|\,\mathcal{E}(\mathbf{x})/(T^3\sqrt{\lambda})$ for $v = 3/4$, with the T=0 and near zone (20) contributions removed. A Mach cone is clearly visible, with an opening half-angle $\theta \approx 50°$.

Hologramm
from P.Chesler,L.Yaffe
(also Gubser et al have detailed papers
On this)

Both groups made amazingly detailed Description of the <u>conical flow</u> from AdS/CFT=>

Note that it is not hydro but a full soluiton: the shape of the wave is correct Even at micro scales

subsonic



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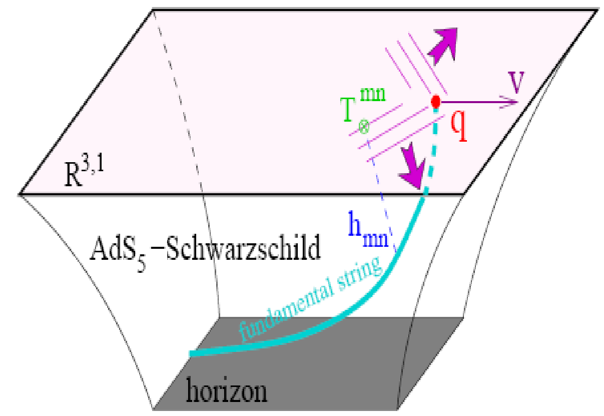

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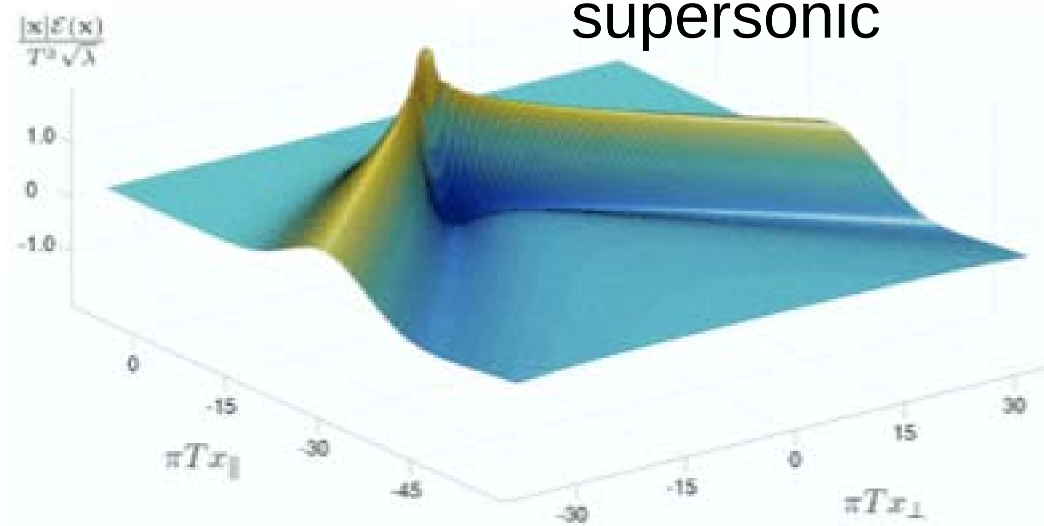

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Left: P.Chesler,L.Yaffe
Up- from Gubser et al

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

Part II
Non-equilibrium physics in AdS/CFT setting

Gravity dual for the heavy ion collisions

- **T=0 AdS metric** corresponds to extreme BH

(**mass is minimal for its charge** => no horizon)

- As collision creates "debris", they fall, add extra mass and form a **non-extreme BH with a horizon => T**
- **Advantages: naturally dissipative+ classical**
- Expanding/cooling fireball= departing b.h. horizon,
- Different geometries: 1+d, d=1,2,3 collapses

Sin,ES and Zahed 04,

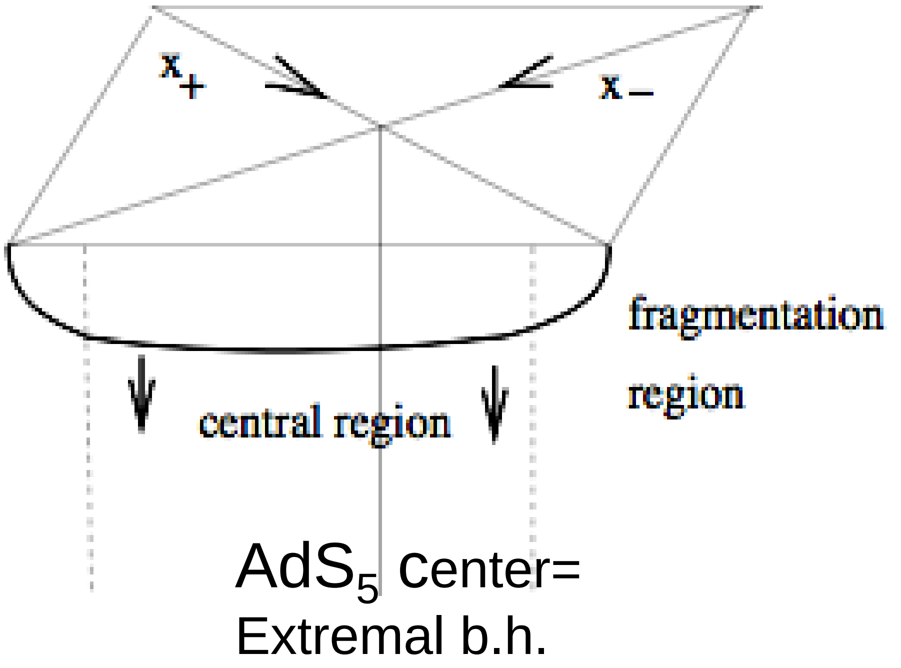
- BH is longitudinally stratching 1+1 - rapidity independent example Janik-Peschanski 05 proposed **late-time** solution
- 1+3 approaching/departing BH without entropy change
  Gubser et al, 06

Gravity dual to the (heavy quark) 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
- Strings are flux tubes , they don’t break



Toward the AdS/CFT gravity dual for High Energy Collisions: I.Falling into the AdS

Shu Lin and Edward Shuryak

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

- EOM and solutions for various objects flling in AdS: a “stone”, closed circular string, 3d membrane
- Falling open string, with ends fixed x=(+/-)vt
- Analytic scaling solution z=tau f(y), only exist till v<1/2 and remains stable till v<.27 or so
- Numerical solutions: near free fall in the middle

Scaling solution is analytic, but we found it **gets unstable at** endpoint rapidity **Y>.27 !**

proper time and spatial rapidity variables

$$\tau = \sqrt{t^2 - x^2}, \quad y = \frac{1}{2} log(\frac{t-x}{t+x})$$

$$S = -\frac{R^2}{2\pi\alpha'} \int \frac{\tau d\tau dy}{z^2} \sqrt{1 - \left(\frac{\partial z}{\partial \tau}\right)^2 + \frac{\left(\frac{\partial z}{\partial y}\right)^2}{\tau^2}} \quad (15)$$

Before solving the corresponding equation in full, we will first discuss "scaling" solutions in the separable form

$$z(\tau, y) = \frac{\tau}{f(y)} \quad (16)$$

Action at small v gives **"AdS/CFT Ampere law"**

$$V = 0.2285 \frac{(1 + 0.6830\, v^2)\sqrt{g^2 N}}{L} \quad (24)$$

The coefficient in front (the leading term at $v \to 0$) coincides with the well known coefficient of static Maldacena potential

- Looking for classical stability: Lyapunov exponents $\delta g(\tau, y) = e^{\lambda \bar{\tau}} \psi(y)$

$\lambda(10^{-2})$	1.2+222.1i	0.78+265.7i	0.38+299.5i	0.12+346.4i
Y	0.37	0.33	0.30	0.27

Which instability in the hologramm does it correspond to?
Is it generic or present for this solution only?

Non-scaling solution at large y studied numerically: it develops cusps

- There is a well seen fragmentation and nearly-free falling central parts
- Stress self-focuses at the ``corners" =>cusps

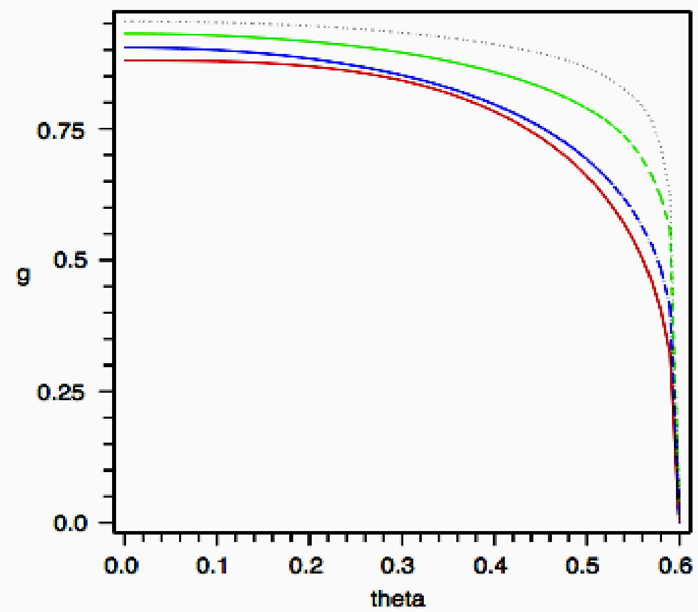


FIG. 8: The dynamics of the string(half) $g(\tau, y)$ with $y = 0.6$. The profiles from the innermost to the outermost correspond to $\tau = 1$(solid red),$\tau = 2$(dotted blue),$\tau = 4$(dashed green), $\tau = 8$(dot-dashed black).

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.

- What observer on the boundary sees is a **``holographic image**" of this process,
- => can be calculated using time-dependent Green function for linearized Einstein eqns, as in examples above

How does it look for a falling string?

Is it hydro-like explosion or not?

- Holographic imag
of a falling string
shows **an explosion**
- *(as far as we know the first time-dependent hologramm)*
- **Which however cannot be reprensented as hydro fluid => anisotropi pressure in th ``comoving frame”**

- T_{00} , T_{oi}

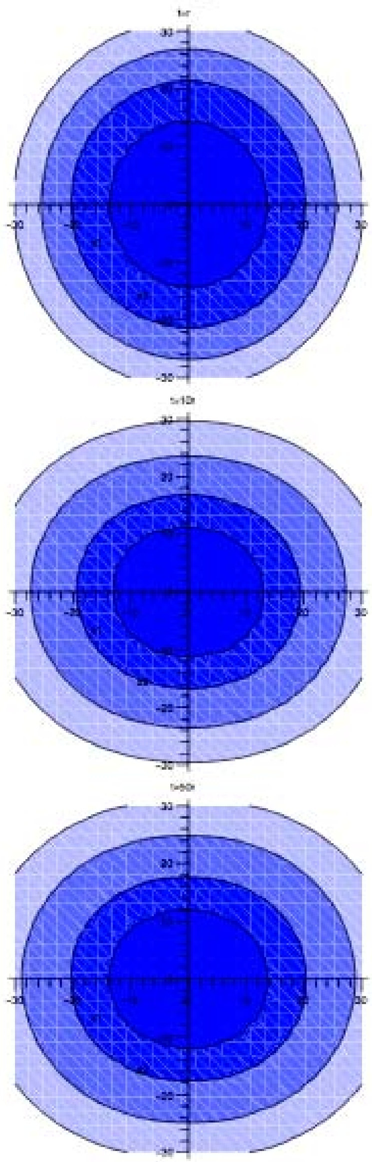


FIG. 1: (color online) The contours of energy density T^{00}, in unit of $\frac{2\sqrt{\lambda}}{f_0^2\pi^2}$, in $x_1 - x_2$ plane at different time. The three plots are made for $t = r$, $t = 10r$ and $t = 50r$ from top to bottom. The magnitude of T^{00} is represented by the color,

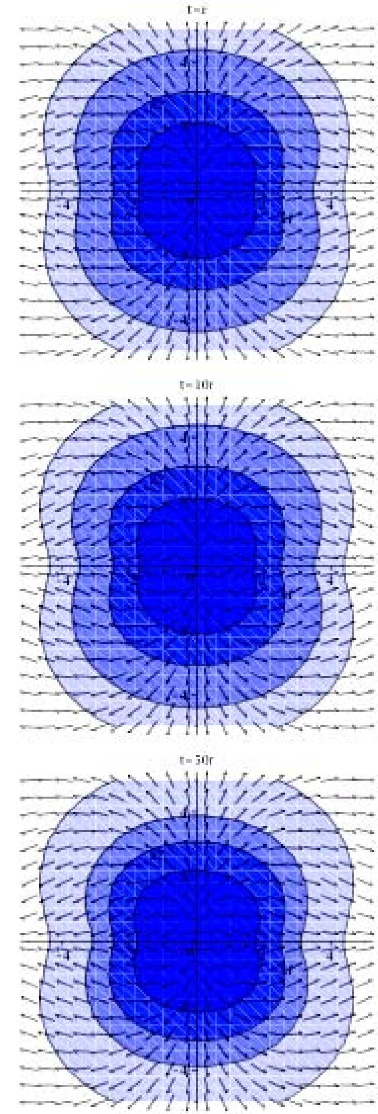


FIG. 2: (color online)The contours of momentum den sity T^{0i}, in unit of $\frac{2\sqrt{\lambda}}{f_0^2\pi^2}$, in $x_1 - x_2$ plane at differen time. The three plots are made for $t = r$, $t = 10$ and $t = 50r$ from top to bottom. The magnitude i represented by color, with darker color corresponding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

Many strings falling together

- Imagine 2 walls of heavy quarks => multiple strings falling => no dependence on transverse coordinates x_2,x_3
- The falling object is thus not a string but 3d membrane-like, to be called M_m (matter or string membrane)
- **(Are there instabilities or other dissipative phenomena in it, creating entropy?)**

Including gravity of debries:

=> another (more famous) membrane M_h,

(of the “membrane paradigm”)

is hovering just above the horizon

- Horizon not only has **Hawking T and Bekenstein S**, but many other universal properties
- T.Damour (1978..1982) introduced **electric conductivity, shear and bulk viscosity**
- K.Thorne et al (1980s) put it in the form in which many astrophysical problems were solved
- (e.g. planets rotating around and plunging into B.H., accretion discs with magnetic and electric fields, thermal atmospheres etc)

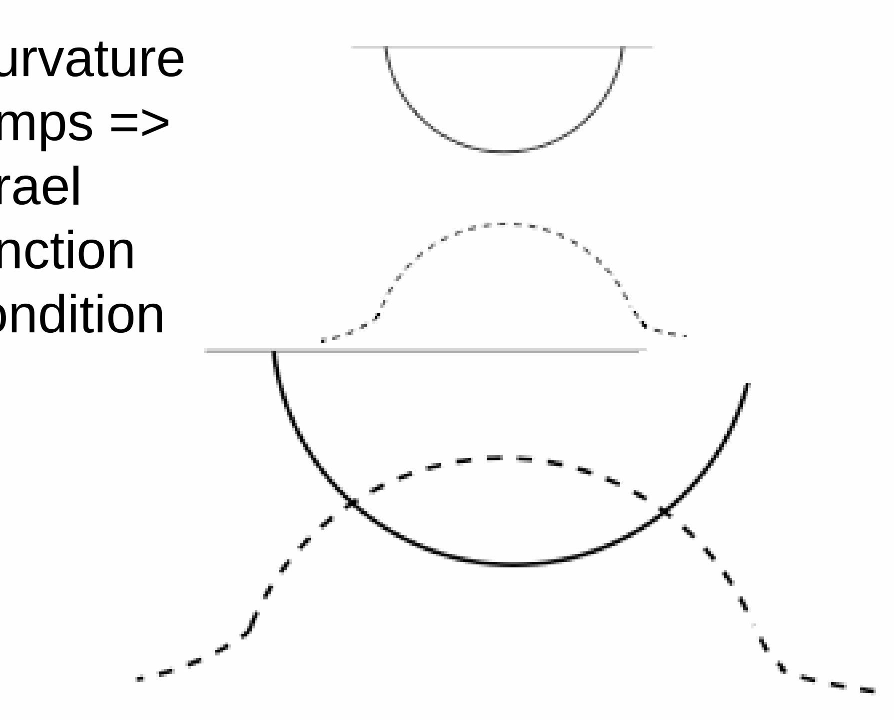
How falling strings got equilibrated?

- Solid line is a falling "matter membrane" M_m, its ends have +/- v
- Dashed lines are **horizon membrane M_h** which bulge upward due to gravity of Mm
- One possible simplification => flat

falling membranes

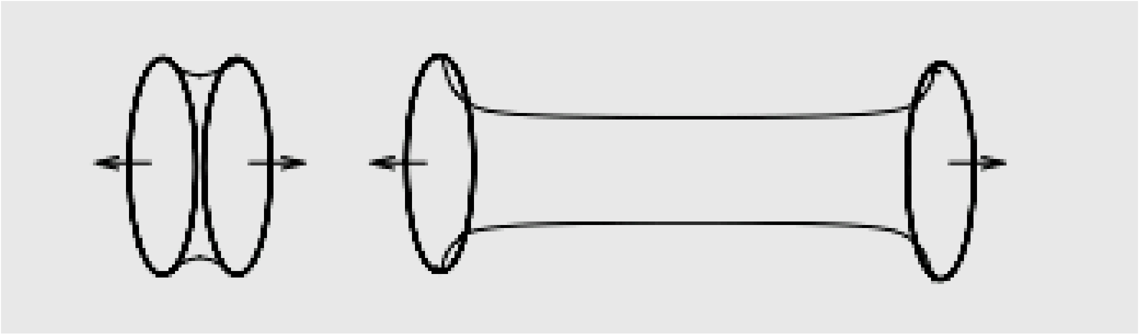
Before equilibration

Curvature jumps => Israel junction condition



After part of M_m gets Substituted by M_h, observer at z=0 sees hydro and near-thermal T_{munu}

The membrane which is longitudinally stretched is being contracted, as soap film



- M_h is 3-dimensional in 5d, if stretched longitudinally a la Hubble x=vt, it moves in $z=O(t^{1/3})=1/r$ so **$A=4S= O(x\ r^3)$=const (Janik et al)**
- **In next order in time there is dissipation induced by the M_h viscosity**

Before conclusions, homework problems

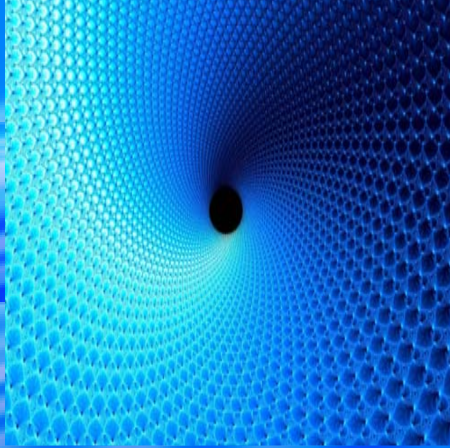
- Are there (analogs of filamentation etc?) **instabilities for falling strings? Unruh T?**
- **If so, what part of Bekenstein entropy do they create?**
- **Calculate the other part, created by viscosity of the horizon membrane**
- **Using AdS/CFT, answer the dilemma of top-down vs down-up cascades**

(collisional vs bremmstrahlung equilibration)

Conclusions

- Strongly coupled QGP is produced at RHIC T=(1-2)Tc
- This is the region where transition from magnetic to electric dominance happen
- at T<1.4 Tc of magnetic dominance => E-flux tubes
- Good liquid because of magnetic-bottle trapping **the lowest viscosity for 50-50% electric/magnetic plasma**

- AdS/CFT => natural applications to finite-T nonconfining and Strongly coupled, sQGP
- RHIC data on transport (eta,D), ADS/CFT and classical MD all qualitatively agree!
- **Are these two pictures related? LHC**



Non-equilibrium AdS/CFT has Advantages:
(i) classical
(ii)t-odd dissiptive boundary cond. At horizon
(iii) 30 years or work on grav.collapse
Holograms of 2 membranes…