

RHIC and AdS/CFT

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Outline of the talk

- brief description of the RHIC experiment
- working definition of (s)QGP
- AdS/CFT as a theoretical tool
- three main themes/topics (involving AdS/CFT):
 - elliptic flow (indication of early equilibration)
 - viscosity bound $\frac{\eta}{s} \geq \frac{1}{4\pi} \frac{\hbar}{k_B}$.
 - jet quenching
- string duals of $N = 1$ SQCD-like theories, simple solution for $N_f = 2N_c$.
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Brief description of RHIC (Brookhaven, Long Island)

- circular nucleus-nucleus collisions, main ring has 38 km circumference, c.o.m energy per nucleon $\sqrt{s} \sim 200 GeV$, centrality=0/head-on collisions, one gets ~ 20 particles per incident nucleus.
- STAR collaboration, "Critical assessment of the evidence from RHIC collisions for QGP", nucl-ex/0501009
Au-Au ring collisions: theory-experiment comparison suggest that dense, rapidly thermalizing matter is produced which is characterized by:
 - **initial energy density** above critical value predicted by LQCD for establishment of QGP (RHIC operates at $1.5T_c < T < 2T_c$, $T_c \sim 170 MeV$).
 - **nearly ideal fluid flow**, interactions with very short mean free path at a stage (presumably) preceding hadron formation.
 - **opacity to jets**.

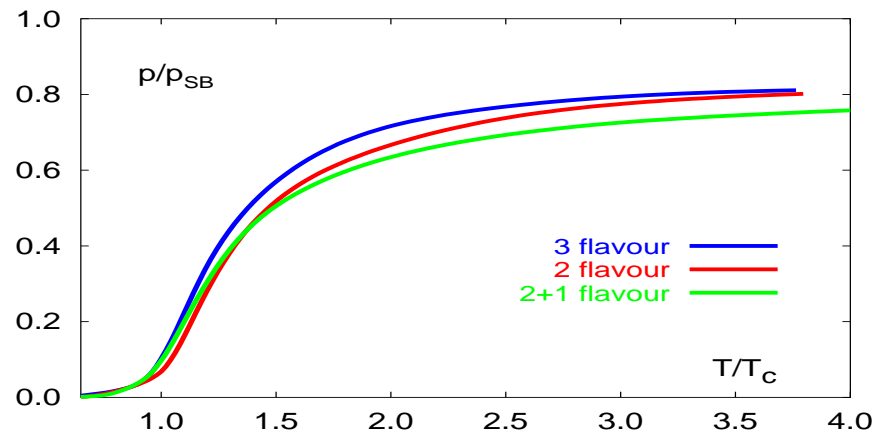
Definition of QGP/Goal of RHIC

- All of this seems to be consistent with formation of a **strongly coupled Quark-Gluon-Plasma** (sQGP) at an early stage. BUT: no observation of "smoking gun" onset of a transition to a new form of matter.
- STAR working definition of QGP:
A (locally) **thermally equilibrated** state of matter in which quarks and gluons are **deconfined** from hadrons, so that color d.o.f. become manifest over **nuclear**, rather than nucleonic, volumes; at a temperature above QCD deconfinement "transition" @ around T_c .
- **Goal of RHIC:**
 - create matter above deconfinement crossover.
 - study its properties.

How to study properties of QGP at RHIC?

- For **static**, i.e. thermodynamic, properties, **lattice QCD** is a great tool.
- For **transport** properties (e.g. viscosities), **LQCD** is not suitable, because real-time dynamics requires Minkowski formulation (to this date only Euclidean).
- For decades, expectation was that QGP is a weakly coupled (non-interacting) gas of quarks and gluons. Experiments now seem to indicate that QGP is a **strongly coupled, nearly ideal fluid**. \implies **perturbative QCD** not applicable. Is this surprising?

Lattice simulation of energy density



- at $T \sim \text{few } T_c$, coupling not small.
- LQCD shows ϵ/T^4 is $\sim 80\%$ of its value in ideal-gas-QGP, just above $T_c \implies$ interactions only 20
- Compare to $\mathcal{N} = 4$ SYM plasma: $\epsilon/T^4 \sim 75\%$, but interactions very strong, $\frac{\eta}{s} = \frac{1}{4\pi}$, ideal hydro.

AdS/CFT as a theoretical tool

- Need theoretical tool to study strongly coupled gauge theories \implies **AdS/CFT**, duality between type IIB strings on $AdS_5 \times S^5$ and $\mathcal{N} = 4$ **SYM** in $d = 4$, very different from **QCD**!
- Comparison between QCD and $\mathcal{N} = 4$ SYM.

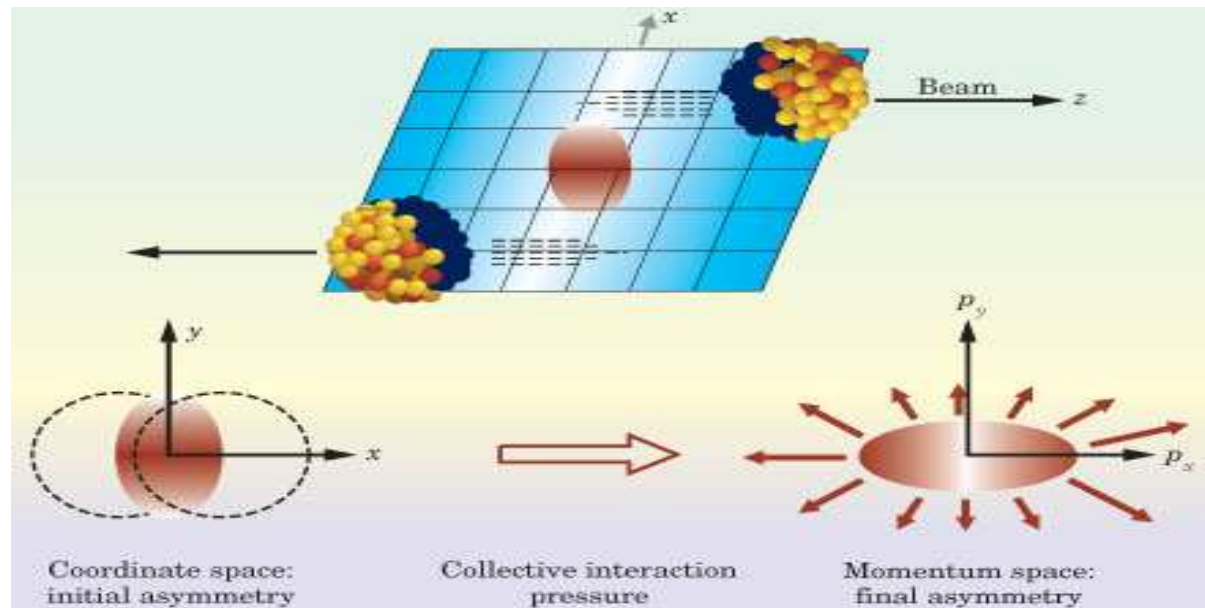
	QCD	$\mathcal{N} = 4$ SYM
$T = 0$	confinement, discr. spec., scattering	conformal, contin. spec., no S-matr., SUSY
$T \gtrsim T_c$	str. cpled plasma w/ fundamental matter	str. cpled plasma w/ adjoint matter
$T \gg T_c$	runs to weak coupling	remains strongly coupled

Three main examples

- **Elliptic flow**, indication of early equilibration, ideal hydrodynamics correctly predicts data (but: Caution!)
- **Universal viscosity bound** $\frac{\eta}{s} \geq \frac{1}{4\pi}$.
- **Jet quenching**

Elliptic flow

- non-central collisions \implies almond-shaped fire ball.
- If interactions strong (enough), equilibration, pressure gradients (shaped charge) leading to collective expansion, elliptic flow pattern.



Elliptic flow

- Quantify in terms of v_i harmonics:

$$\frac{dN}{d\phi} = \frac{v_0}{2\pi} + \frac{v_2}{\pi} \cos 2\phi + \frac{v_4}{\pi} \cos 4\phi + \dots$$

- In case elliptic flow happens early, before almond circularizes through free streaming $\implies v_2 \neq 0$.
- This is observed at RHIC, the experimental value being correctly reproduced by **ideal hydrodynamics** simulations for $p_T < 2\text{GeV}$. Assumption: (local) **thermal equilibrium**.
- Means that ideal hydro works fine by $t \sim 0.6 - 1\text{fm}$.

Challenge to theory

- How can equilibrium occur so quickly? Strong interactions? Strong color fields?
- Also means: small shear viscosity η , $\frac{\eta}{s} \lesssim \mathcal{O}(1/10)$. Measure of how far away you are from perfect fluid.

Comparison of $\frac{\eta}{s}$ in $\mathcal{N} = 4$ SYM and QCD

- $\mathcal{N} = 4$ SYM supersymmetric but SUSY broken at $T \neq 0$.
- $\mathcal{N} = 4$ SYM has 16 adjoint d.o.f., QCD has 2, cancels in ratio.
- $\mathcal{N} = 4$ SYM has no fundamental d.o.f., but Buchel, Liu and Starinets showed that $\frac{\eta}{s} = \frac{1}{4\pi}$ in **any** theory with a gravity dual.
- $\mathcal{N} = 4$ SYM is conformal, QCD is not, however QGP thermodynamics quite conformal (e.g. speed of sound $v_s \sim \frac{1}{\sqrt{3}}$) for $2T_c < T < 10T_c$.
- $\frac{\eta}{s} = \frac{1}{4\pi}$ for $\lambda = g^2 N_c \rightarrow \infty$, but corrections positive \implies conjecture: lower bound (Kovtun, Son, Starinets).
- $\frac{\eta}{s}$ calculated for $N_c \rightarrow \infty$, corrections not known.

Calculation of $\frac{\eta}{s}$ from AdS/CFT

- Consider finite T $\mathcal{N} = 4$ SYM in large N_c and large $\lambda = g_{YM}^2 N_c$ limit, dual to near-extremal D3 black branes in type IIB SUGRA.

- shear viscosity can be computed from gravity

- **Kubo's formula** relates η to equilibrium correlation functions:

$$\eta = \lim_{\omega \rightarrow 0} \frac{1}{2\omega} \int d^4x e^{i\omega t} \langle [T_{xy}(t, \vec{x}), T_{xy}(0)] \rangle = \lim_{\omega \rightarrow 0} \frac{1}{\omega} \text{Im} G^R(\omega).$$

- R.h.s related to absorption cross-section of low-energy **gravitons** by the branes:

$$\sigma_{abs}(\omega) = -\frac{2\kappa^2}{\omega} \text{Im} G^R(\omega).$$

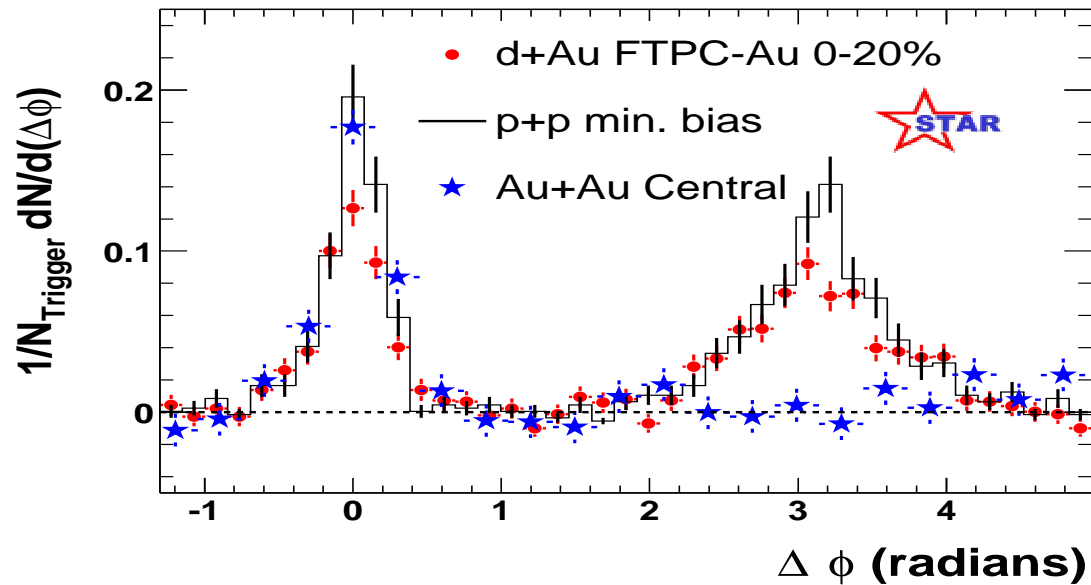
$$\implies \eta = \frac{\sigma_{abs}(0)}{2\kappa^2} = \frac{\sigma_{abs}(0)}{16\pi G}.$$

Calculation of $\frac{\eta}{s}$ from AdS/CFT

- Study small perturbations of background metric $g_{MN} = g_{MN}^{(0)} + h_{MN}$.
- σ_{abs} calculated classically by solving linearized wave eq. for h_{xy} .
- h_{xy} in fact satisfies wave eq. for massless scalar, $\square h_x^y = 0$.
- For scalars, $\sigma_{abs}(0)$ known to be equal to horizon area.
- **Result:** $\frac{\eta}{s} = \frac{A}{16\pi G} \cdot \frac{4G}{A} = \frac{1}{4\pi}$.

Jet quenching

- QGP opaque to hard partons \implies interior jet is getting quenched, away-side suppression at high p_T .



- energy loss depends on jet quenching parameter $\Delta E = \alpha_s \hat{q} L^2$

Jet quenching

- perturbative QCD (high energy/weak coupling): energy loss due to gluon radiation, but \hat{q}_{pert} fails to match $\hat{q}_{RHIC} \sim 5 \frac{\text{GeV}^2}{\text{fm}}$ at $T = 280 \text{MeV}$ by 1-2 orders of magnitude.
- AdS/CFT result (Liu, Rajagopal, Wiedemann):
 $\hat{q}_{SYM} = 26.7 \sqrt{\alpha N_c} T^3$, with $N_c = 3, \alpha = 0.5, T = 280 \text{MeV} \implies$
 $\hat{q}_{SYM} \sim 3.7 \frac{\text{GeV}^2}{\text{fm}}$.

Jet quenching

- AdS/CFT: "lifetime" of colored probe (heavy quarks) dragged through $\mathcal{N} = 4$ plasma, $t_0 \sim 1 - 2 \text{fm}/c$ consistent with lifetime of QGP of $t_{\text{QGP}} \sim 6 \text{fm}/c$.

Getting closer to QCD

- $\mathcal{N} = 4$ SYM to $\mathcal{N} = 1$ SYM.
Maldacena-Núñez solution: gravity solution corresponding to large number of $NS5$ branes wrapped on a 2-sphere \implies pure $\mathcal{N} = 1$ SYM in IR.
- 6 dim. LST/NS5-brane theory (reduces to 6D $\mathcal{N} = 4$ SYM in IR)
wrap NS5-branes on S^2
- 4 dim. (pure) $\mathcal{N} = 4$ SYM in IR
twist normal bundle of S^2 to preserve only 1/4 SUSY
- 4 dim. pure $\mathcal{N} = 1$ SYM in IR.

Getting closer to QCD

- Casero, Núñez, Paredes: String duals of $\mathcal{N} = 1$ SQCD-like theories.
- take into account backreaction on the space of the N_f D5-branes;
 $N_f \rightarrow \infty$ flavor branes homogeneously smeared along two transverse S^2 s.
- supergravity + branes solutions depend on N_f/N_c .
- CNP found simple solutions of BPS eqs. for $\frac{N_f}{N_c} = 2$.

$\mathcal{N} = 1$ SQCD-like theories

- Unfortunately, CNP solutions do not seem to be **good** gravity duals.
- thermodynamic instabilities, temperature $T = \frac{1}{2\pi\sqrt{\alpha' N_c}}$, typical for LST.
- Bigazzi, Bertoldi, Cotrone, Edelstein study hydrodynamics of these solutions (hep-th/0702225).
- Alternative: Find **stable** $N_f = 2N_c$ solution first, then study its properties.
- We found a solution that seems to be **stable** for both small and large r and have horizon-dependent temperature. But thermodynamics quite complicated.