Quark-Gluon Plasma *vs.* Strings and Black Holes

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- QGP and Strong Coupling QCD

  QCD Hydrodynamics from Strings?

- Gauge/Gravity correspondence

  Introduction

- "Holography" for S^4QCD Hydrodynamics

  Emergence of a Black Hole Geometry

- Some Examples

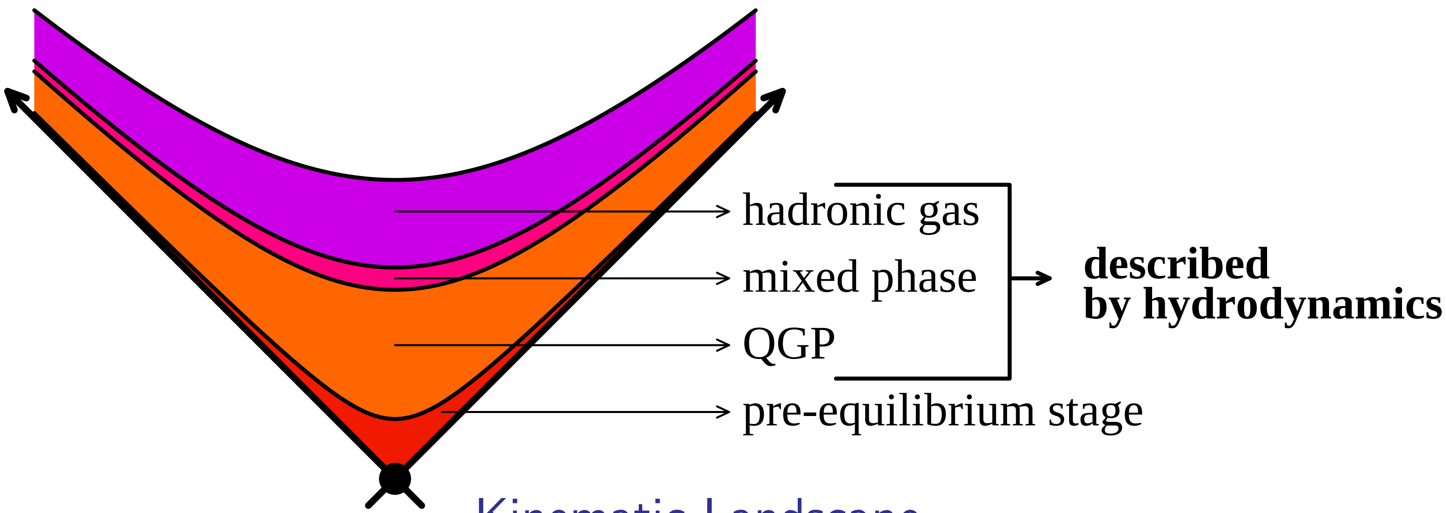
  AdS/CFT $\Rightarrow$ nearly perfect fluid, small viscosity

- Fast Isotropization/Thermalization at strong coupling

  Stability and Transitions of a Moving Black Hole

- Conclusions and (Many+1) Open Problems

QGP formation and Relativistic Hydrodynamics



Kinematic Landscape

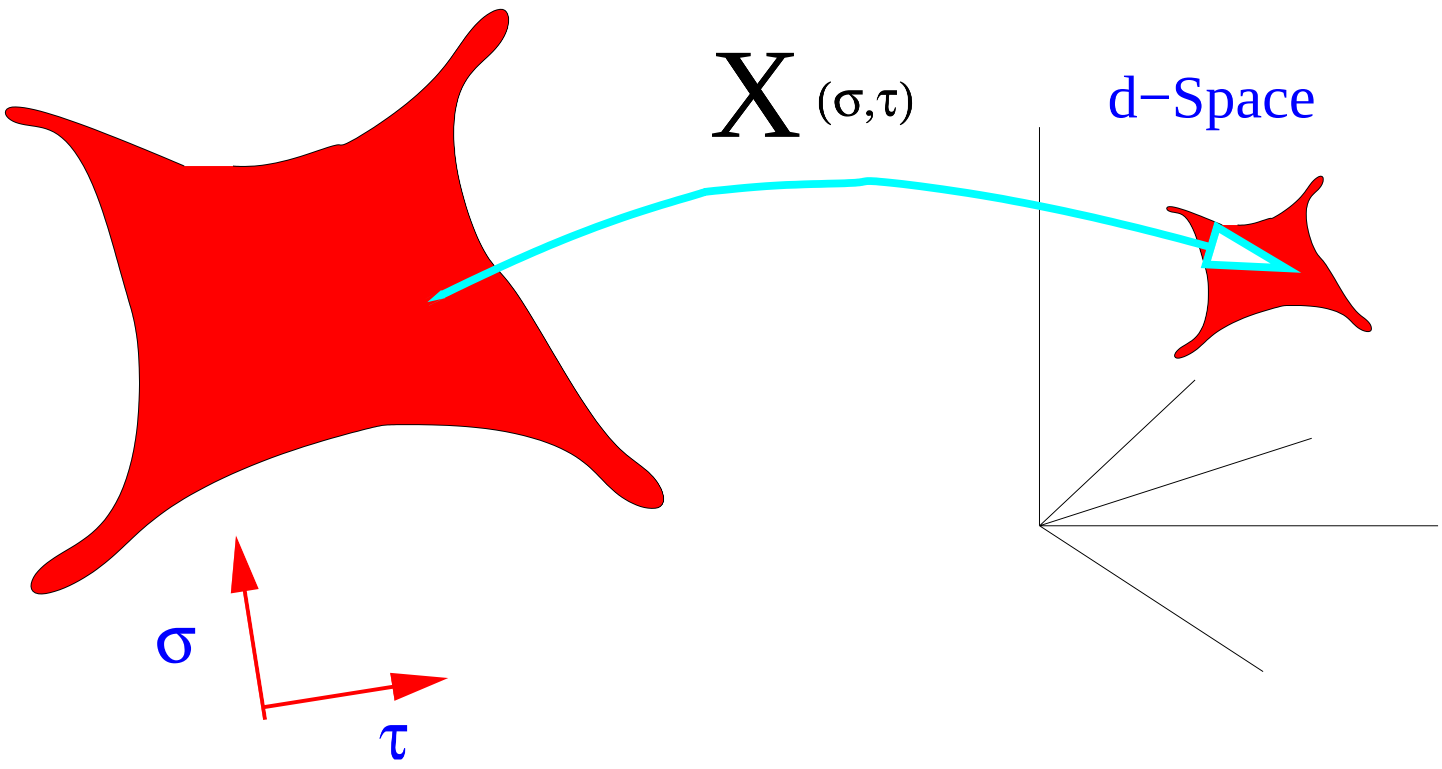
$$\tau = \sqrt{x_0^2 - x_1^2} \; ; \; \eta = \frac{1}{2} \log \frac{x_0 + x_1}{x_0 - x_1} \; ; \; x_T = \{x_2, x_3\}$$

"Abstracted" from Data **:**

- QGP: (Almost) Perfect fluid behaviour $\Rightarrow$ small Viscosity
- Fast QGP Formation
- Jet Quenching, Drag force,...

QGP at Strong Coupling : What Strings can tell us?

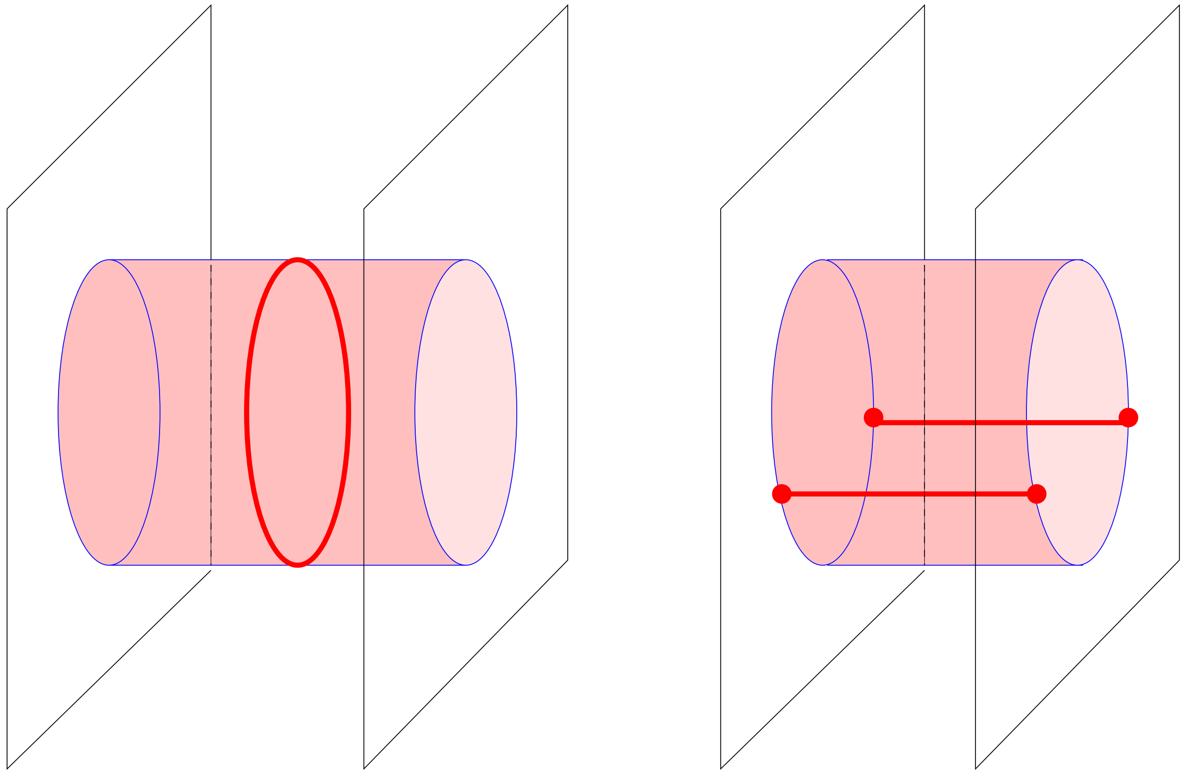
String Apparatus



World Sheet $\longrightarrow$ Target Space

The Gauge-Gravity Correspondence

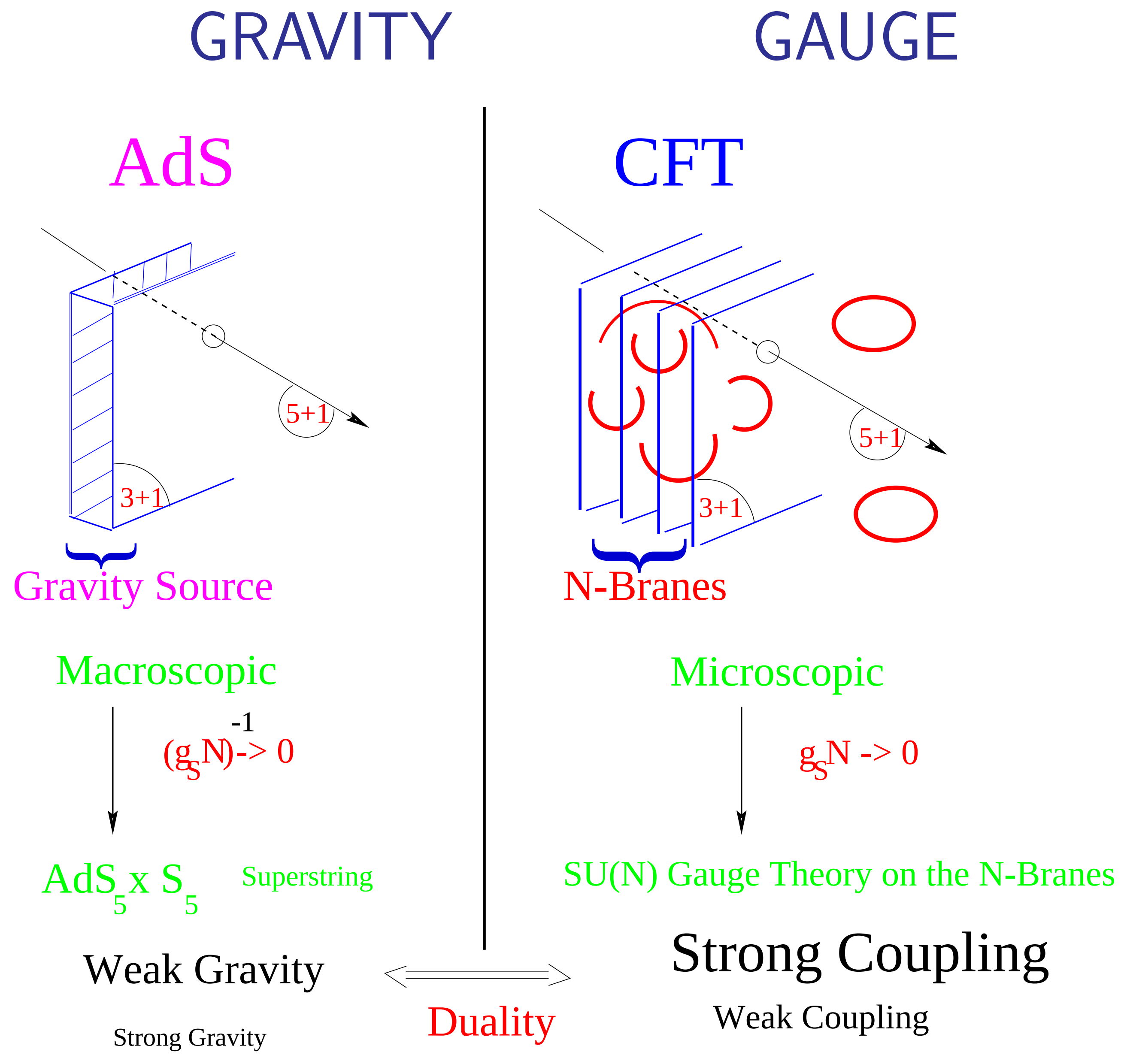
Open $\Leftrightarrow$ Closed String duality



$$\left\{ \begin{array}{rcl} Closed\ String & \Leftrightarrow & 1 - loop\ Open\ String \\ Gravity & \Rightarrow & Gauge \\ D{-}Brane\ \text{“}Universe'' & \Rightarrow & Open\ String\ Ending \\ Large/Small\ Distance & \Rightarrow & AdS/CFT\ Correspondence \end{array} \right.$$

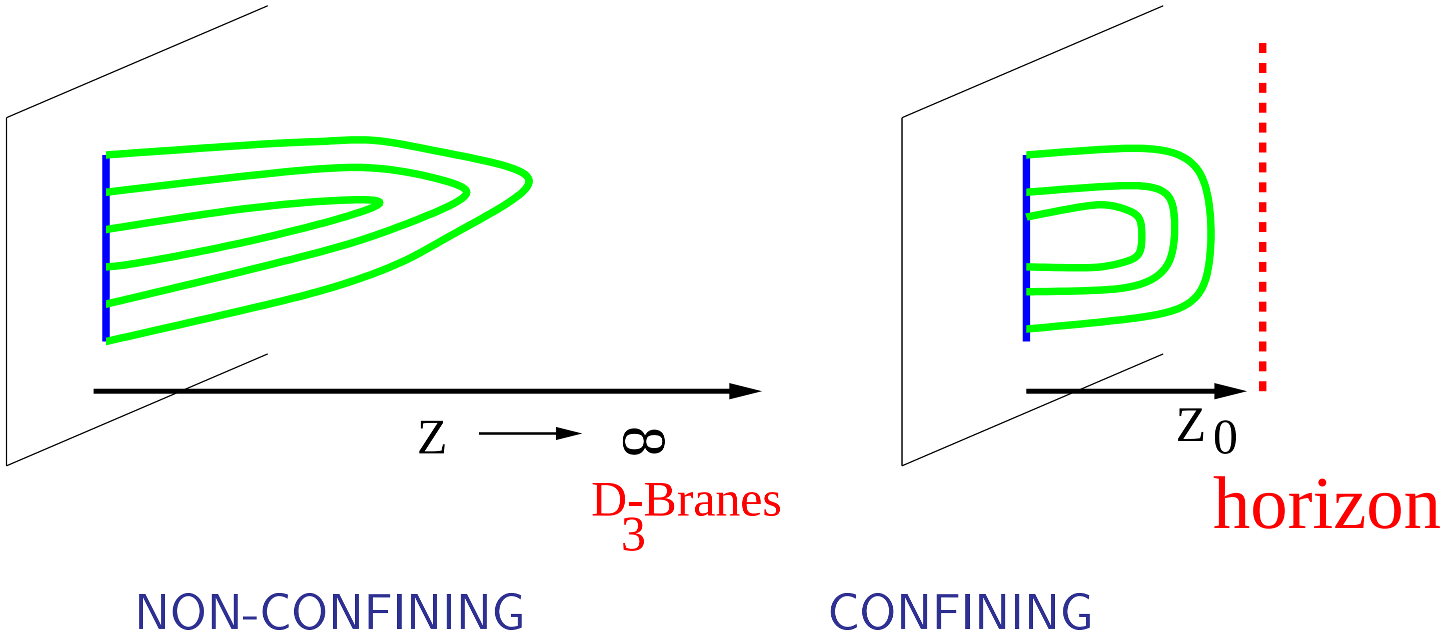
AdS/CFT Correspondence

J.Maldacena (1998)



HOLOGRAPHY

- Holographic Principle: Brane/Bulk correspondence



- Brane $\rightarrow$ Bulk: Holographic Renormalization

K.Skenderis (2002)

$$g_{\mu\nu} = g^{(0)}_{\mu\nu}(=\eta_{\mu\nu}) + z^2 g^{(2)}_{\mu\nu}(=0) + z^4 \langle T_{\mu\nu}\rangle + \mathbf{z^6} \ldots +$$

$+\mathbf{z^6}\ldots+$: from Einstein Eqs.

Perfect Fluid $\Leftrightarrow$ 5d BLACK HOLE

Balasubramanian,de Boer,Minic; Myers

- 4d Perfect Fluid (PF) "on the 4d brane": $\epsilon = 3p$

$$\langle T_{\mu\nu} \rangle \propto g^{(4)}_{\mu\nu} = \begin{pmatrix} 3/z_0^4 = \epsilon & 0 & 0 & 0 \\ 0 & 1/z_0^4 = p_1 & 0 & 0 \\ 0 & 0 & 1/z_0^4 = p_2 & 0 \\ 0 & 0 & 0 & 1/z_0^4 = p_3 \end{pmatrix}$$

- From (Resummed) Holographic Renormalisation

Janik,R.P.

$$ds^2 = -\frac{1 - \tilde{z}^4/\tilde{z}_0^4}{\tilde{z}^2} dt^2 + \frac{dx^2}{\tilde{z}^2} + \frac{1}{1 - \tilde{z}^4/\tilde{z}_0^4} \frac{d\tilde{z}^2}{\tilde{z}^2}$$

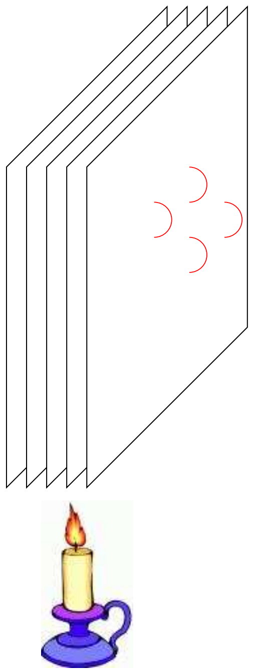
- Static $5-d$ Black Hole with horizon at z_0

$$Temperature: \; T_{BlackHole} =\sim \frac{1}{z_0} = \epsilon^{\frac{1}{4}} = T_{PerfectFluid}$$

$$Entropy: \; S_{BlackHole} \sim Area = \frac{1}{z_0^3} \sim \epsilon^{\frac{3}{4}} = S_{PerfectFluid}$$

Viscosity on the light of duality

Consider a graviton that falls on this stack of N D3-branes
Will be absorbed by the D3 branes.
The process of absorption can be looked at from two different perspectives:



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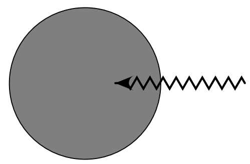


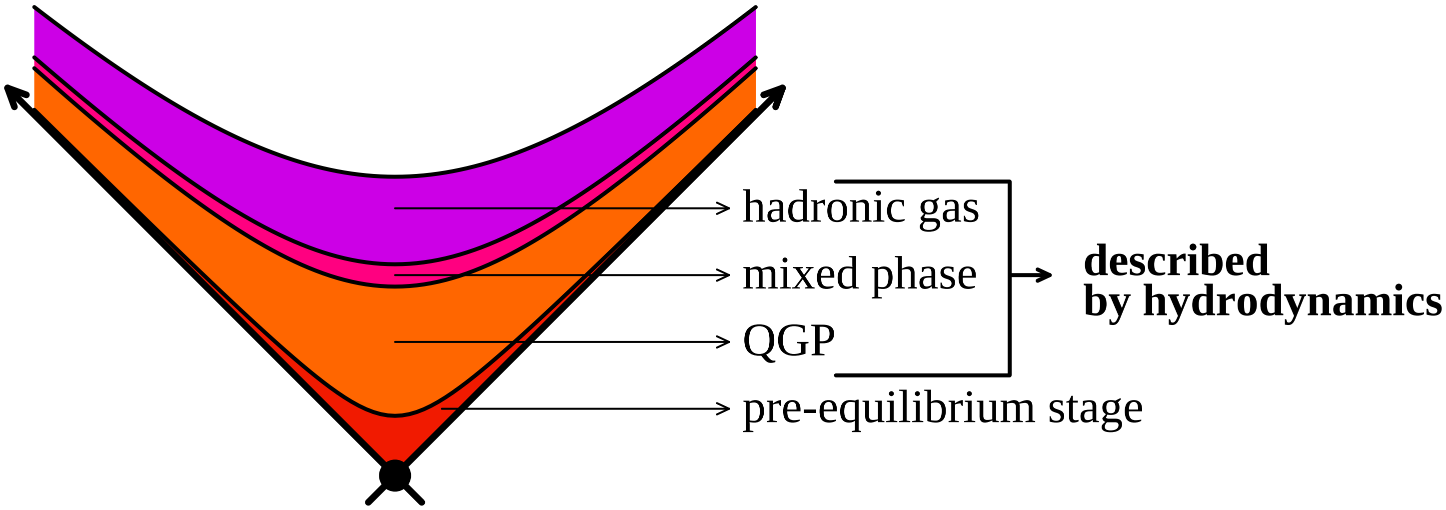
Absorption by D3 branes ($\sim$ viscosity) = absorption by black hole

$$\sigma_{abs}(\omega) \propto \int d^4x \, \frac{e^{i\omega t}}{\omega} \, \langle [T_{x_2x_3}(x), T_{x_2x_3}(0)] \rangle \Rightarrow \frac{\eta}{s} \equiv \frac{\sigma_{abs}(0)/(16\pi \; G)}{A/(4 \; G)} = \frac{1}{4\pi}$$

Static case: Policastro, Son, Starinets (2001)

AdS/CFT: From Statics to Dynamics

R.Janik, RP (2005)



$$\tau = \sqrt{x_0^2 - x_1^2}\ ; y = \frac{1}{2}\log\frac{x_0 + x_1}{x_0 - x_1}\ ;\ x_T = x_2, x_3$$

Questions

- Boost Invariant Flow (JD Bjorken, (1983)): What is the Dual ?
- QGP: Perfect fluid behaviour, why?
- Fast Pre-equilibrium stage, why?

AdS/CFT $\Rightarrow$ Perfect Fluid at large τ

- Boost-invariant T^μ_ν

$$T_{\mu\nu} = \begin{pmatrix} f(\tau) & 0 & 0 & 0 \\ 0 & -\tau^3 \frac{d}{d\tau} f(\tau) - \tau^2 f(\tau) & 0 & 0 \\ 0 & 0 & f(\tau) + \frac{1}{2}\tau \frac{d}{d\tau} f(\tau) & 0 \\ 0 & 0 & 0 & \dots \end{pmatrix}$$

- 1-parameter family of proper-time evolution

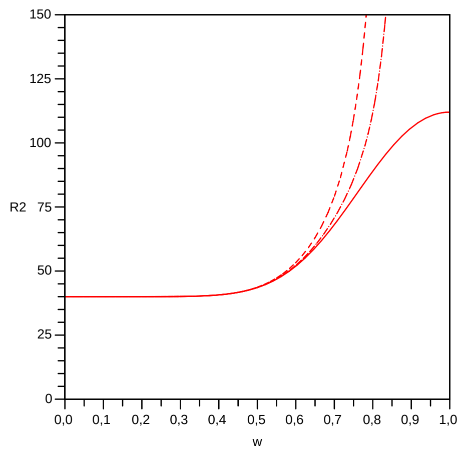
$f(\tau) \propto \tau^{-s}$: $T_{\mu\nu} t^\mu t^\nu \geq 0 \Rightarrow 0 < s < 4$

$f(\tau) \propto \tau^{-\frac{4}{3}}$: Perfect Fluid

$f(\tau) \propto \tau^{-1}$: Free streaming

$f(\tau) \propto \tau^{-0}$: Full Anisotropy $\epsilon = p_\perp = -p_L$

- Curvature Scalar $\mathfrak{R}^2 = R^{\mu\nu\alpha\beta} R_{\mu\nu\alpha\beta}$

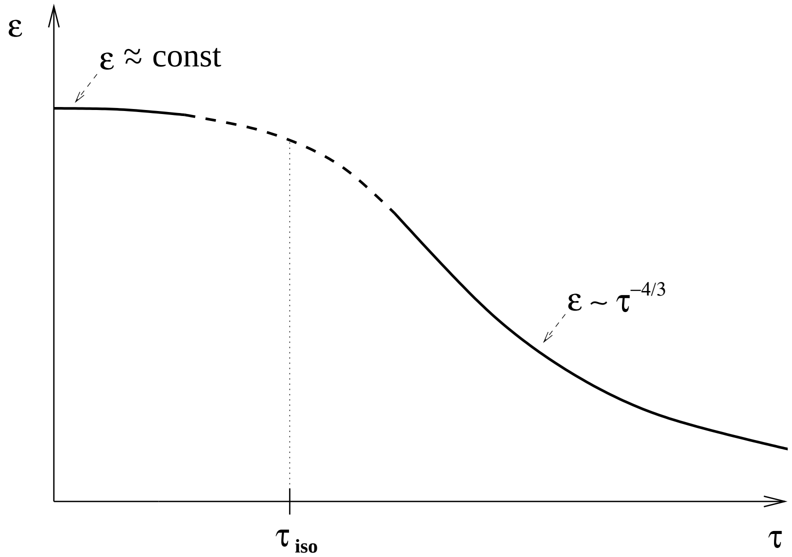


$s = \frac{4}{3} \pm .1$

Nonsingular Dual Geometry $\Leftrightarrow$ Perfect Fluid

AdS/CFT: Anisotropy at small τ

Kovchegov, Taliotis arXiv:0705.1234



Evaluation of The Isotropization/Thermalization time

$$Matching: \; z_h^{late}(\tau) = \left(\frac{3}{e_0}\right)^{\frac{1}{4}} \equiv z_h^{early}(\tau) = \tau$$

$$Isotropization: \; \tau_{iso} = \left(\frac{3N_c^2}{2\pi^2 e_0}\right)^{3/8}$$

$$Evaluation: \epsilon(\tau) \; = \; e_0 \; \tau^{4/3}|_{\tau=.6} \sim 15 \; GeV fermi^{-3}$$

$$\Rightarrow \boxed{\tau_{iso} \sim .3 fermi}$$

Conclusions

In progress:

- Gauge-Gravity Correspondence
  A promising way towards QCD at strong coupling
- Results on AdS/CFT $\rightarrow S^4$QCD Hydrodynamics
  Perfect Fluid, Viscosity, Isotropization
- Other studies
  Jet Quenching, Quark Dragging, and many others...

In outlook:

- Can we go beyond Boost Invariance?
  from Bjorken, Landau to real Hydrodynamics?
- Can we follow the flow from Ions to Hadrons?
  Initial and Final conditions for Hydrodynamic Flow
- From S^4QCD to S^0QCD Hydrodynamics ?
  Can we construct the "Dual" of the actual QGP?

EXTRA SLIDES

More on AdS$_5$

- D_3-brane Solution of Super Gravity:

$$ds^2 = f^{-1/2}(-dt^2 + \sum_1^3 dx_i^2) + f^{1/2}(dr^2 + r^2 d\Omega_5)$$

"On-Branes $\times$ Out-Branes"

$$f = 1 + \frac{R^4}{r^4} \; ; \; R^4 = 4\pi g_{YM}^2 \alpha'^2 N$$

- "Maldacena limit": Strong coupling

$$\frac{\alpha'(\rightarrow 0)}{r(\rightarrow 0)} \rightarrow z \; , \; R \; fixed \; \Rightarrow g_{YM}^2 N \rightarrow \infty$$

$$ds^2 = \frac{1}{z^2}(-dt^2 + \sum_{1-3} dx_i^2 + dz^2) + R^2 d\Omega_5$$

Background Structure: AdS$_5$ $\times$ S_5

The Moving Black Hole

- Existence of a Dynamical Scaling

$$\boxed{v = \frac{z}{\tau^{1/3}}}$$

- Asymptotic metric

$$\boxed{ds^2 = \frac{1}{z^2}\left[-\frac{\left(1-\frac{e_0}{3}\,\frac{z^4}{\tau^{4/3}}\right)^2}{1+\frac{e_0}{3}\,\frac{z^4}{\tau^{4/3}}}d\tau^2 + \left(1+\frac{e_0}{3}\,\frac{z^4}{\tau^{4/3}}\right)\left(\tau^2 dy^2 + dx_\perp^2\right)\right] + \frac{dz^2}{z^2}}$$

- Black Brane Moving off in the 5th dimension

$$Horizon: \; z_h(\tau) = \left(\frac{3}{e_0}\right)^{\frac{1}{4}} \cdot \tau^{\frac{1}{3}} \; .$$

$$Temperature: \; T(\tau) \sim \frac{1}{z_h} \sim \tau^{-\frac{1}{3}}$$

$$Entropy: \; S(\tau) \sim Area \sim \tau \cdot \frac{1}{z_h^3} \sim const$$