

# Quark-Gluon Plasma, Strings and Gauge/Gravity Correspondence

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- QGP and Strong Coupling QCD

*QCD Hydrodynamics from Strings?*

- Gauge/Gravity correspondence

*Introduction*

- “Holography” for  $S^4$ QCD Hydrodynamics

*Emergence of a Black Hole (Brane) Geometry*

- Some (not all!) Examples

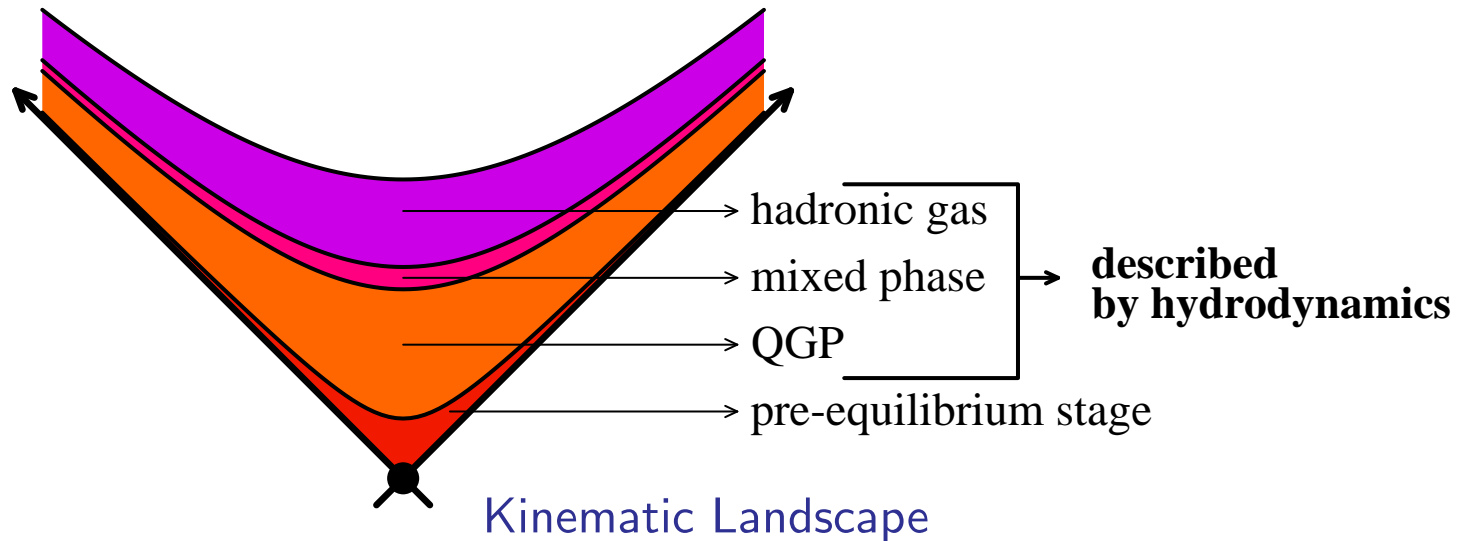
*AdS/CFT  $\Rightarrow$  nearly perfect fluid, viscosity*

- Fast Isotropization/Thermalization at strong coupling

*Stability and Transitions of a Moving “Black Brane”*

- Conclusions and (Many+1) Open Problems

# QGP formation and Relativistic Hydrodynamics



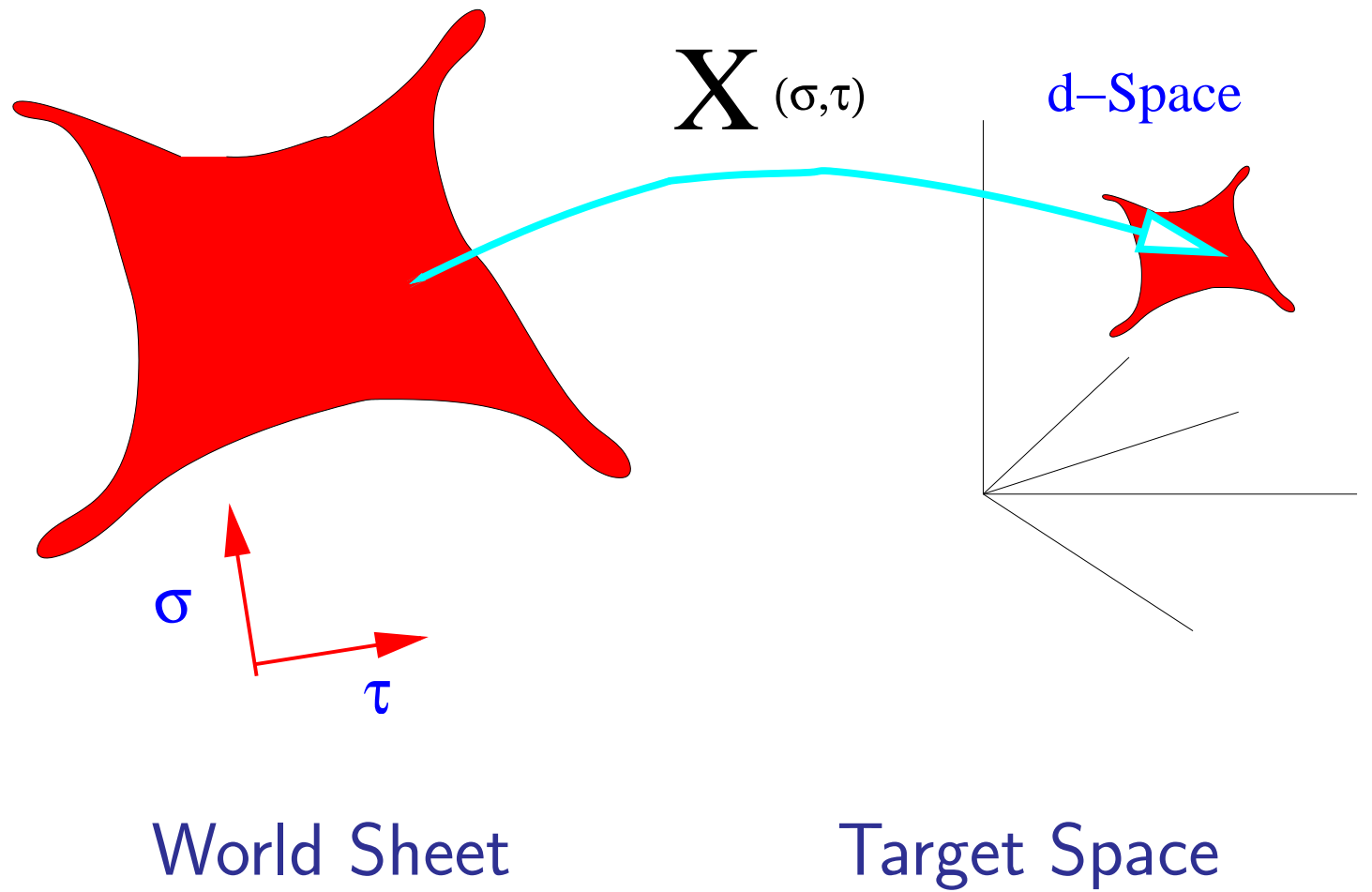
$$\tau = \sqrt{x_0^2 - x_1^2} ; \eta = \frac{1}{2} \log \frac{x_0 + x_1}{x_0 - x_1} ; x_T = \{x_2, x_3\}$$

“Abstracted” from Data :

- QGP: (Almost) Perfect fluid behaviour  $\Rightarrow$  small Viscosity
- Fast QGP Formation
- (Not covered) Jet Quenching

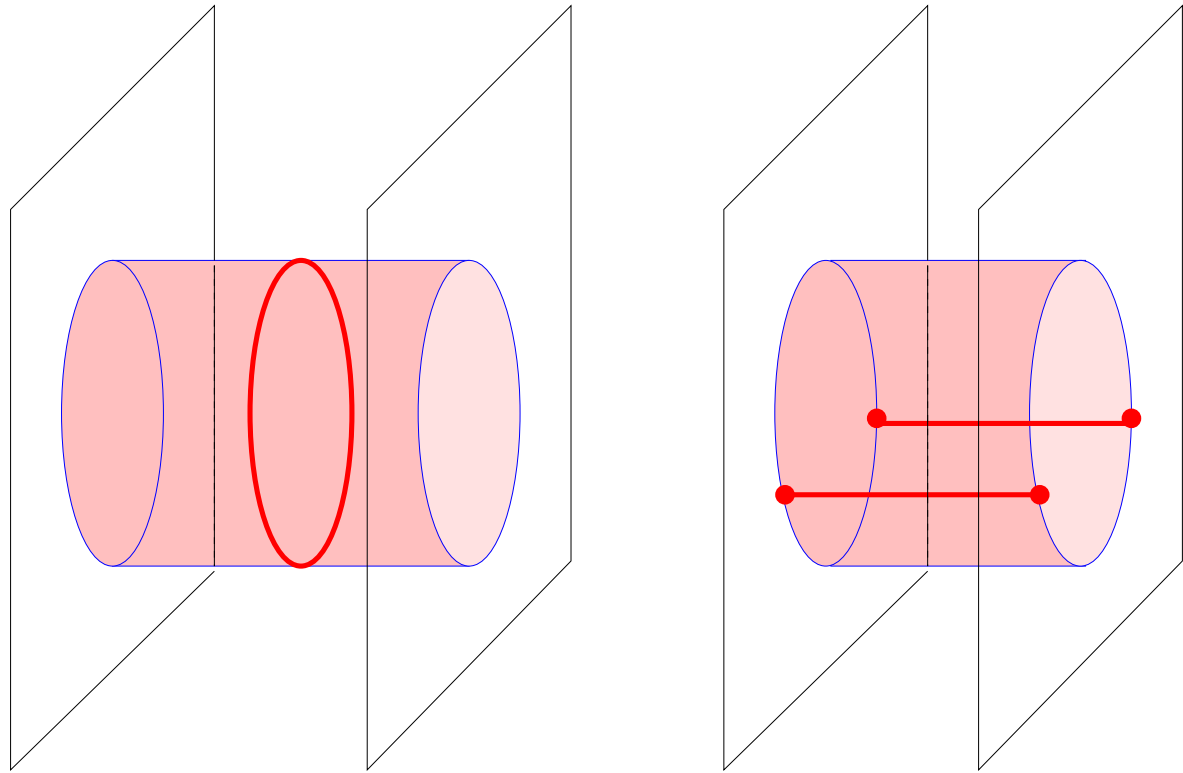
QGP at Strong Coupling : What Strings can tell us?

# String Apparatus



# The Gauge-Gravity Correspondence

Open  $\Leftrightarrow$  Closed String duality



*Closed String*  $\Leftrightarrow$  *1-loop Open String*

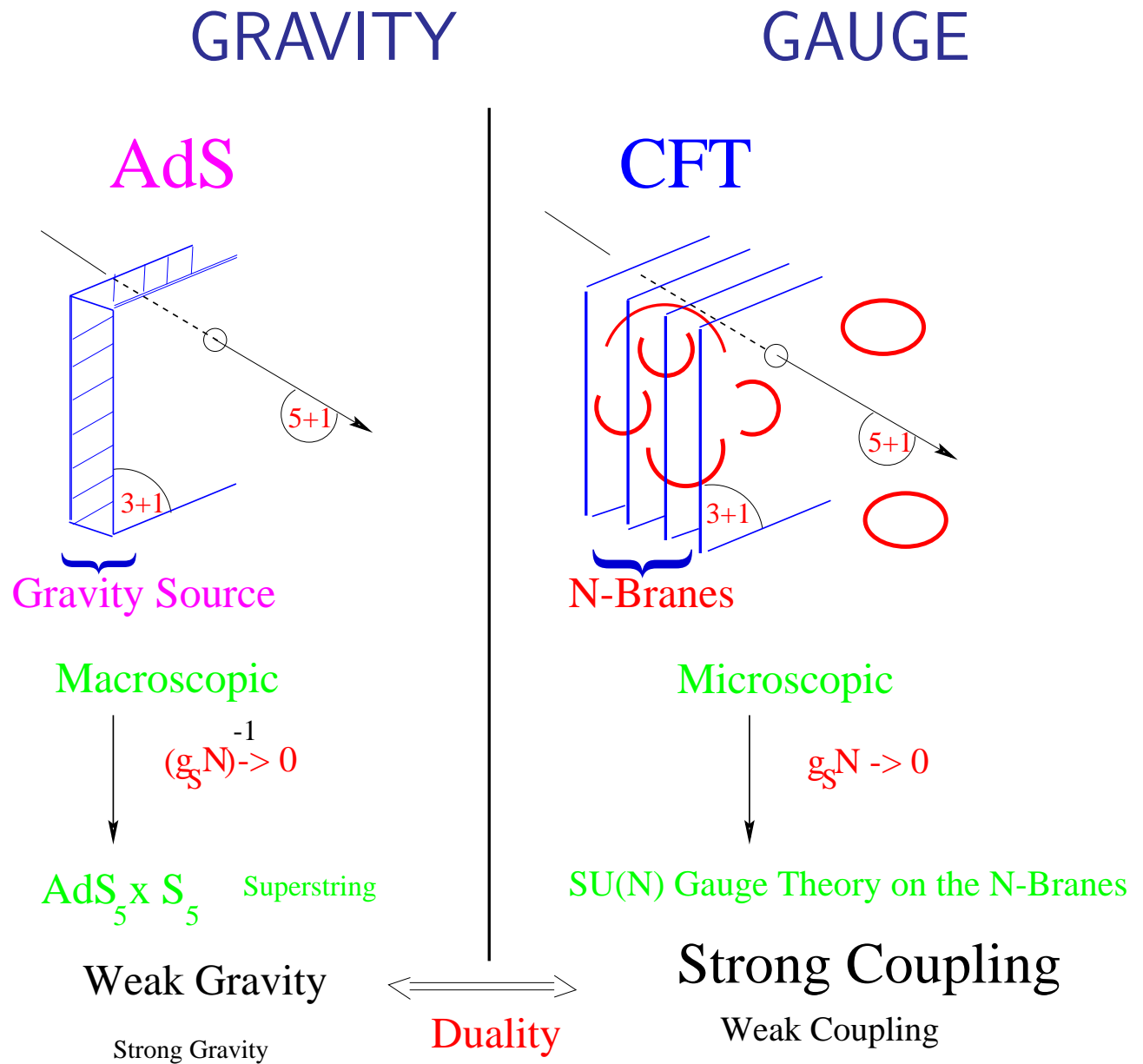
*Gravity*  $\Rightarrow$  *Gauge*

*D-Brane "Universe"*  $\Rightarrow$  *Open String Ending*

*Large/Small Distance*  $\Rightarrow$  *AdS/CFT Correspondence*

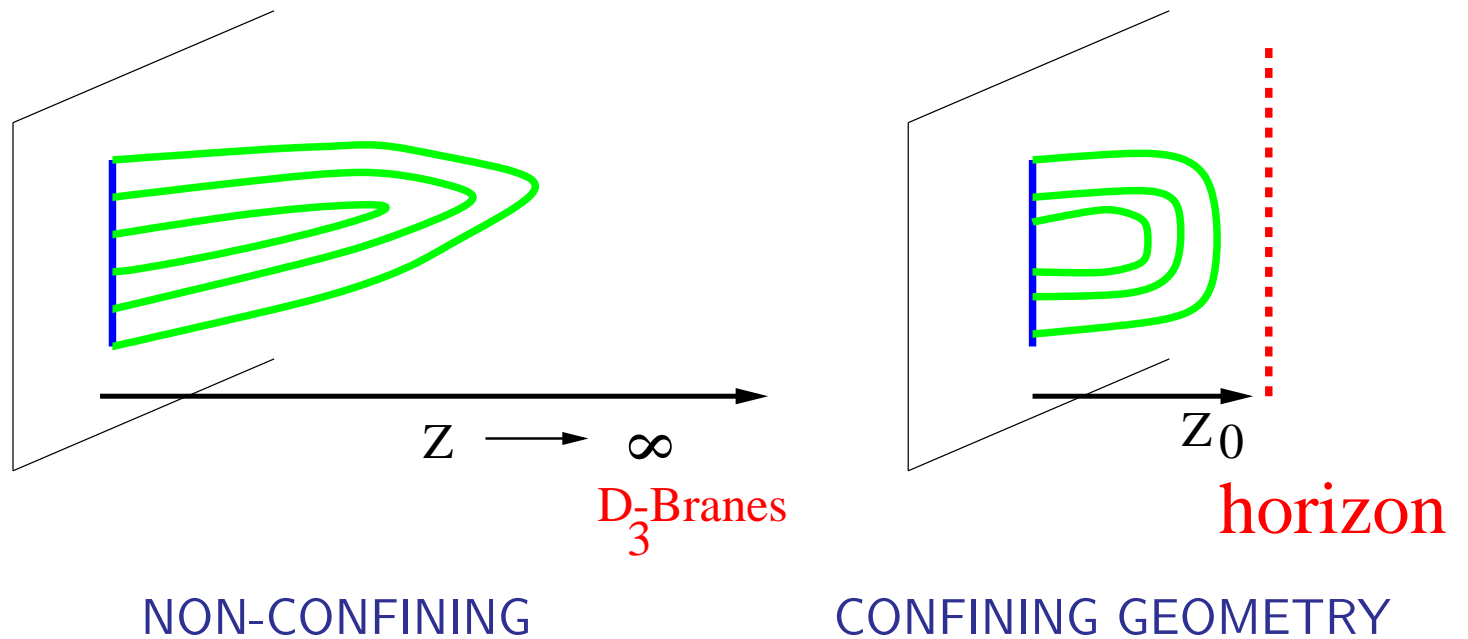
# AdS/CFT Correspondence

J. Maldacena (1998)



# HOLOGRAPHY

- Holographic Principle: Brane/Bulk correspondence



- Brane  $\rightarrow$  Bulk: Holographic Renormalization

K. Skenderis (2002)

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

$+z^6 \dots +$ : from Einstein Eqs.

# Perfect Fluid $\Leftrightarrow$ 5d BLACK HOLE

Balasubramanian, de Boer, Minic; Myers

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

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

- From (Resummed) Holographic Renormalisation

Janik, R.P.

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

- It is indeed the 5-d Black Brane with horizon at  $z_0$

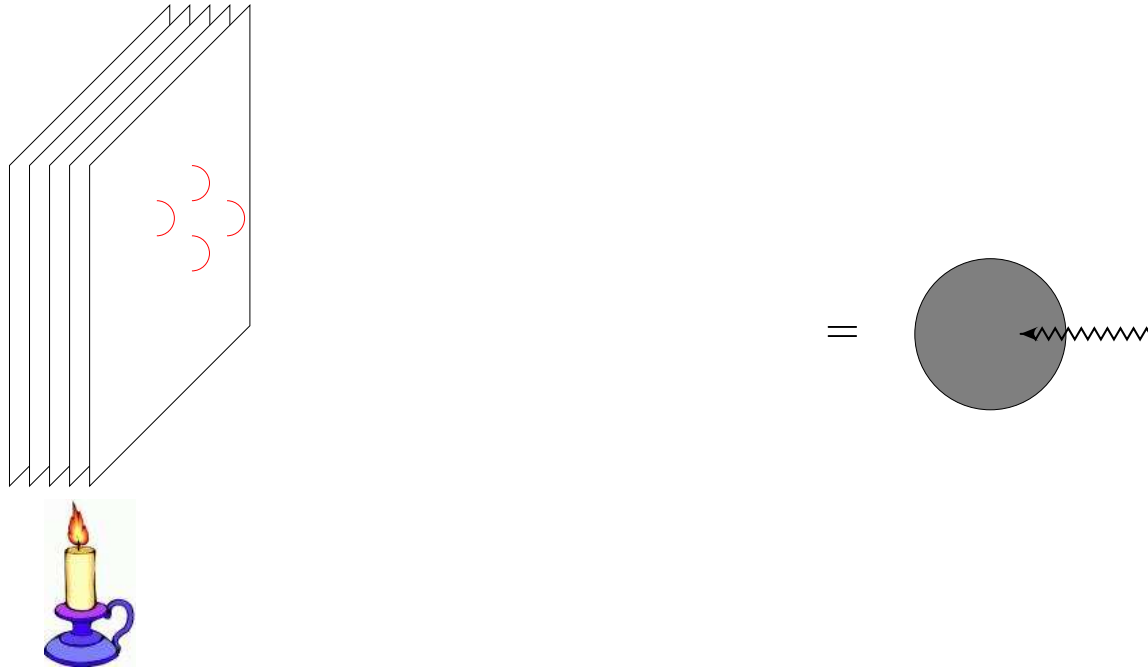
$$\textit{Temperature} : T_{BlackHole} \sim \frac{1}{z_0} = \epsilon^{\frac{1}{4}} = T_{PerfectFluid}$$

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

# 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:



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

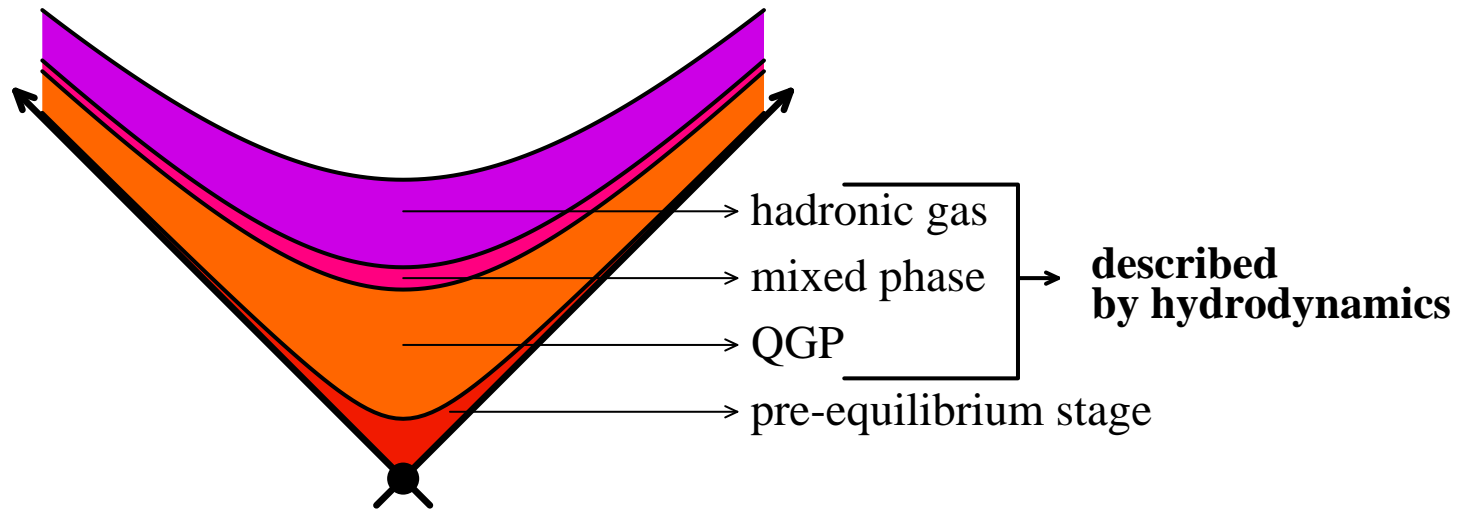
$$\sigma_{abs}(\omega) \propto \int d^4x \frac{e^{i\omega t}}{\omega} \langle [T_{x_2x_3}(x), T_{x_2x_3}(0)] \rangle \Rightarrow \frac{\eta}{s} \equiv \frac{\sigma_{abs}(0)/(16\pi G)}{A/(4G)} = \frac{1}{4\pi}$$

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 $\tau$

- Boost-invariant  $T_{\nu}^{\mu}$

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

- 1-parameter family of proper-time evolution

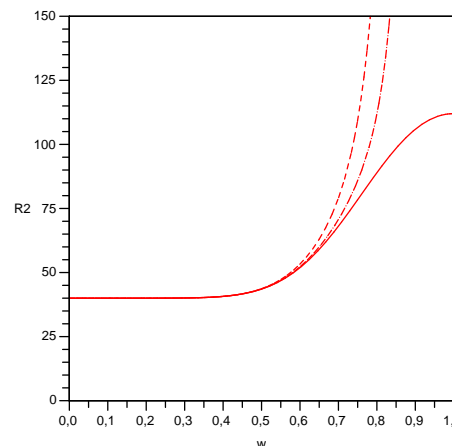
$$f(\tau) \propto \tau^{-s} : T_{\mu\nu} t^{\mu} t^{\nu} \geq 0 \Rightarrow 0 < s < 4$$

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

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

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

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

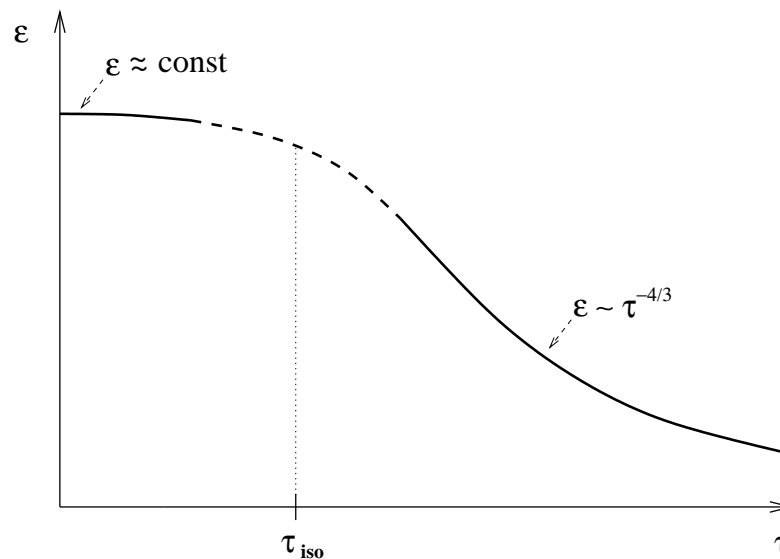


$$s = \frac{4}{3} \pm .1$$

Nonsingular Dual Geometry  $\Leftrightarrow$  Perfect Fluid

# AdS/CFT: Anisotropy at small $\tau$

Kovchegov, Taliotis arXiv:0705.1234



Evaluation of The Isotropization/Thermalization time

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

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

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

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

# 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  $S^4$ QCD to  $S^0$ QCD Hydrodynamics ?  
Can we construct the “Dual” of the actual QGP?

■

EXTRA SLIDES

# More on AdS<sub>5</sub>

- $D_3$ -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 × Out-Branes”

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

- “Maldacena limit”: Strong coupling

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

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

Background Structure: AdS<sub>5</sub> × S<sub>5</sub>

# The Moving Black Hole

- Existence of a Dynamical Scaling

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

- Asymptotic metric

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

- Black Brane Moving off in the 5th dimension

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

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

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