Hydrodynamic Flow of the Quark-Gluon Plasma and Gauge/Gravity Correspondence

Robi Peschanski[a]
(IPhT, Saclay, France)

Aspects of Duality

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- Motivation: Expanding QGP and Strong Coupling QCD
  Hydrodynamics from Strings
- Hydrodynamic flows of the Quark-Gluon Plasma
  Brief Description
- Holographic approach to $\mathcal{N}^4$QCD relativistic Hydrodynamics
  Perfect Fluid ⇔ Moving Black Hole Geometry
- Some Interesting Open QGP Problems
  Isotropization/Thermalization, Initial conditions, Fragmentation regions, Hadronization
- Theoretical Developments and Applications [$cf.$ Janik's talk]
  "Generalized" Hydrodynamic/Gravity Duality

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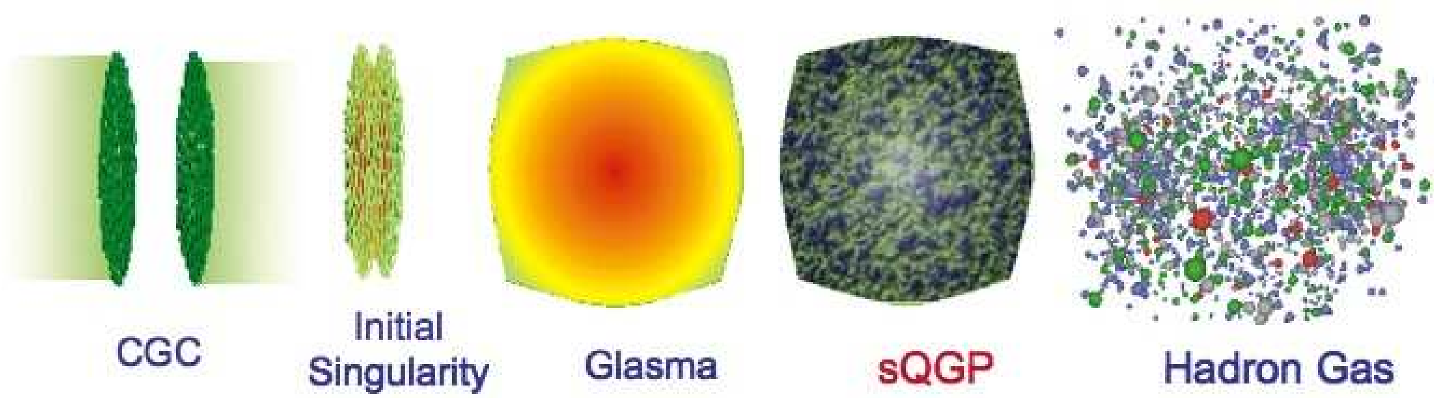
[a] With Romuald Janik, (UJ, Cracow, Poland)

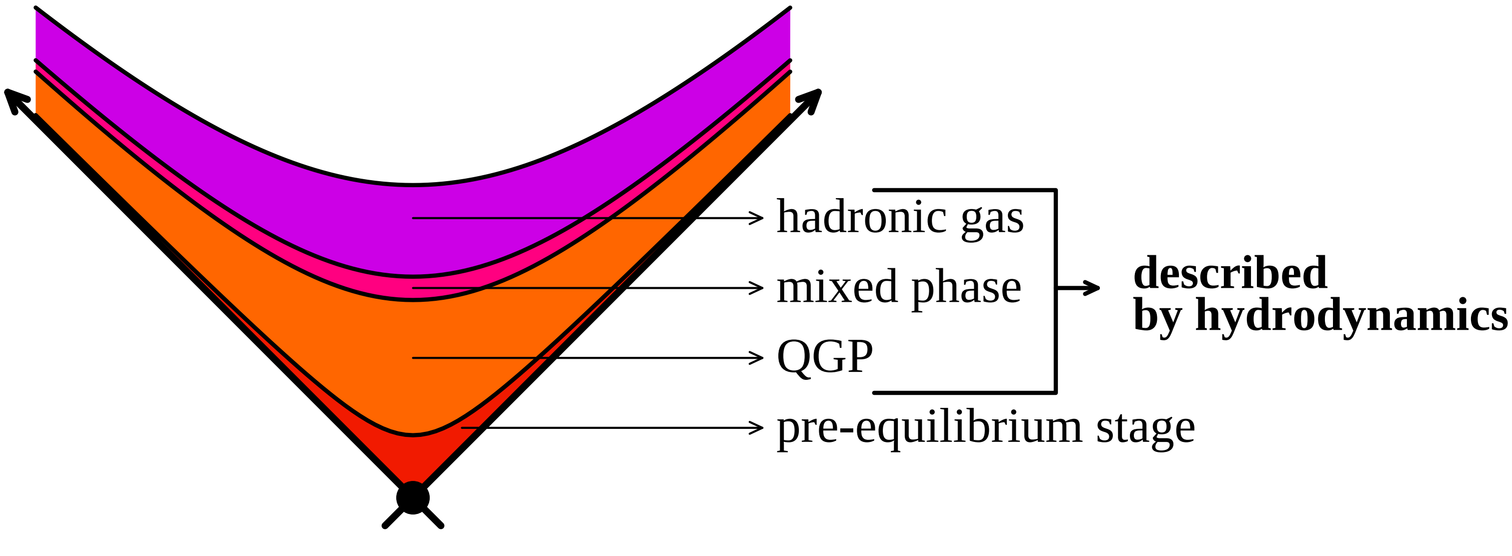
Some References

- arXiv:hep-th/0512162
  "Asymptotic perfect fluid dynamics as a consequence of AdS/CFT"
  R. Janik, R.P.
- arXiv:hep-th/0606149
  "Gauge/gravity duality and thermalization of a boost-invariant perfect fluid"
  R. Janik, R.P.
- arXiv:hep-th/0610144
  "Viscous plasma evolution from gravity using AdS/CFT"
  R. Janik
- arXiv:hep-th/0611304
  "From static to evolving geometries – R-charged hydrodynamics from supergravity"
  Dongsu Bak, R. Janik
- arXiv:hep-th/0703243
  "Viscous hydrodynamics relaxation time from AdS/CFT"
  Michal P. Heller, R. Janik
- arXiv:0709.3910
  "Flavors in an expanding plasma"
  Johannes Große, R. Janik, Piotr Surwka
- arXiv:0706.2108
  " Unified description of Bjorken and Landau 1+1 hydrodynamics"
  A.Bialas, R.A.Janik, R.P.

QGP formation in Heavy-Ion collisions



1+1 Projection



From Experiments to Theory

Abstracted from RHIC Data :

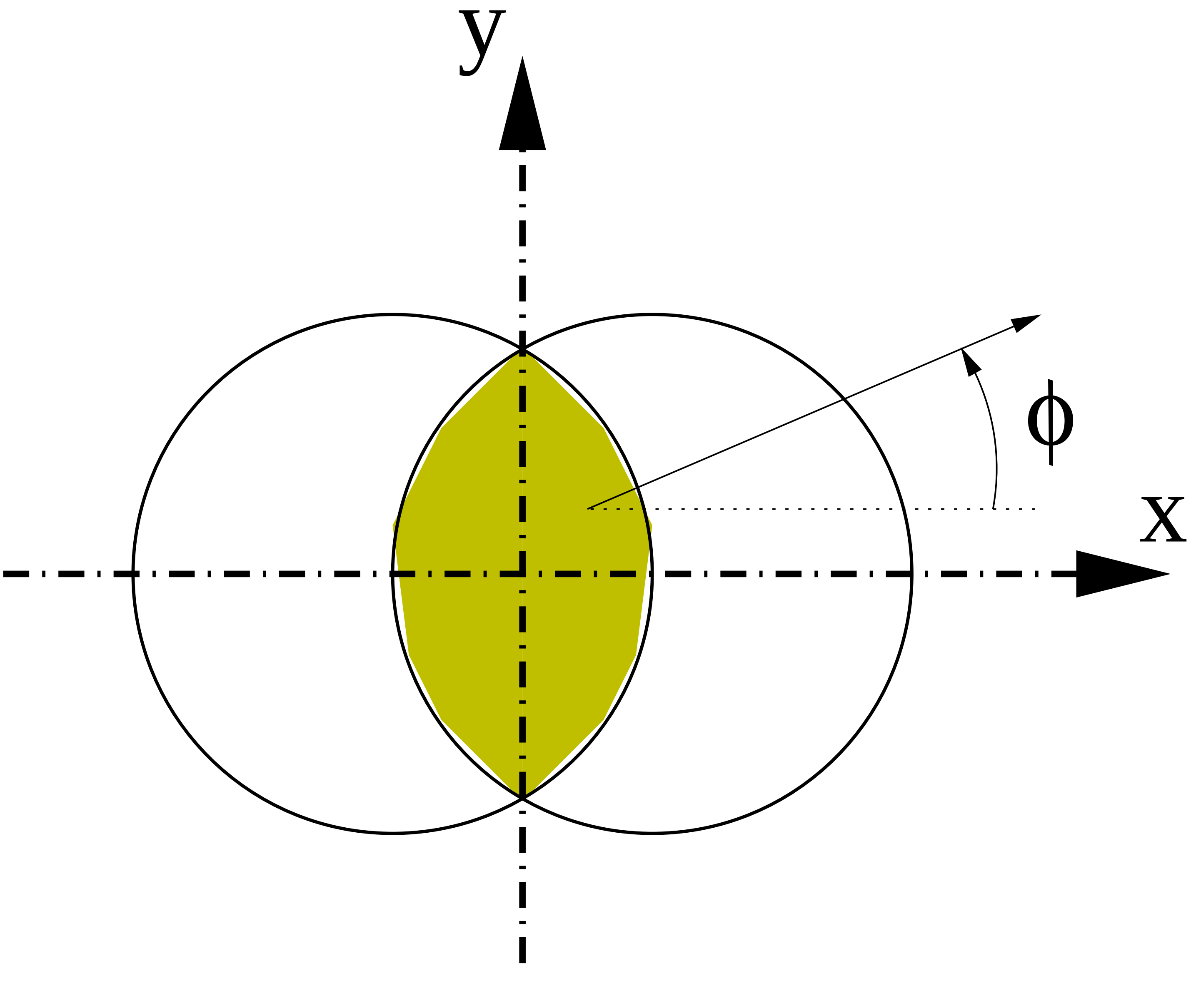
- Evidence for an Hydrodynamic Flow
- QGP: (Almost) Perfect fluid behaviour $\Rightarrow$ small viscosity
- Fast QGP Formation $\Rightarrow$ fast thermalisation/isotropization
- Dependence on Initial and Final conditions

Interest of AdS/CFT :

- QGP as a Strongly Coupled Deconfined phase $\Rightarrow$ N^4QCD
- AdS/CFT as a "laboratory" for QCD
- Gauge/Gravity: a wider concept

QGP at Strong Coupling : What Gauge/Gravity can tell us?

Evidence for an Hydrodynamic Flow

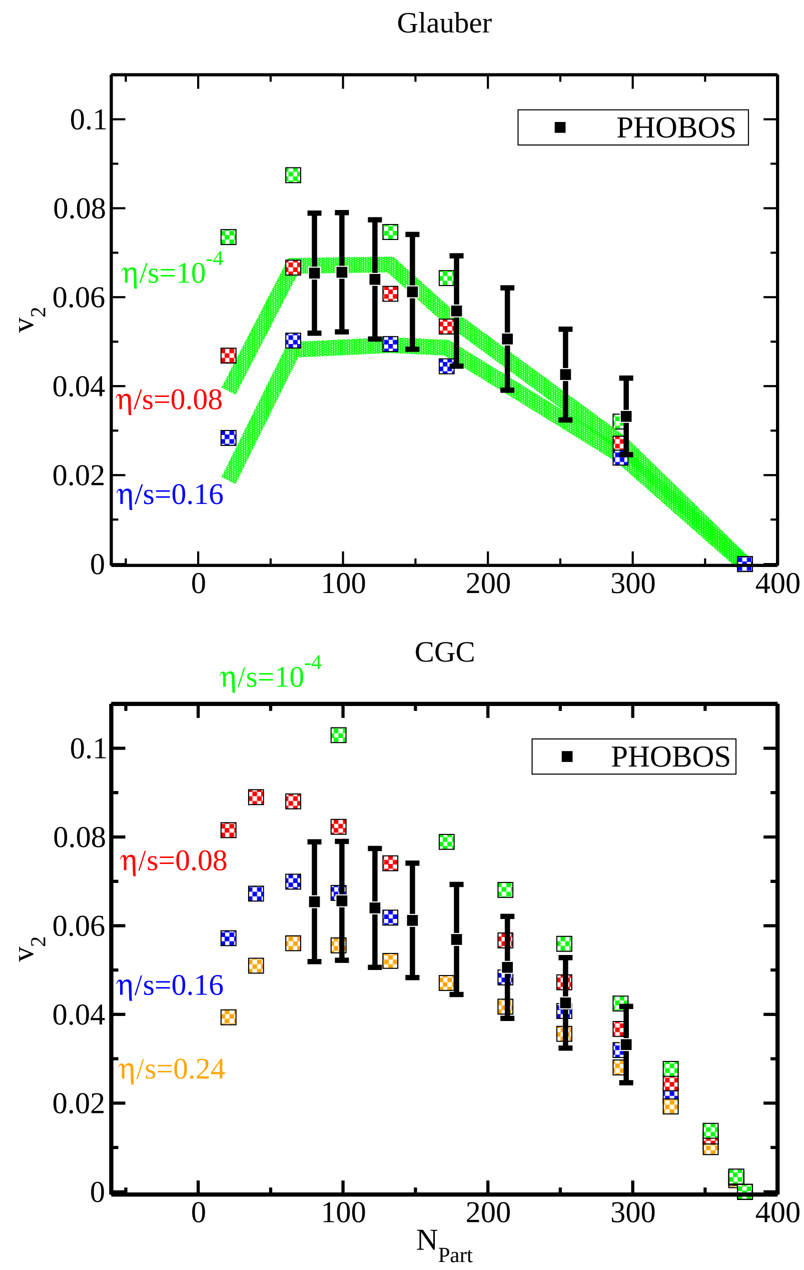


Excentricity: $\boxed{\epsilon = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}}$ $\Rightarrow$ Anisotropic Pressure

Elliptic Flow

Ollitrault (1992)

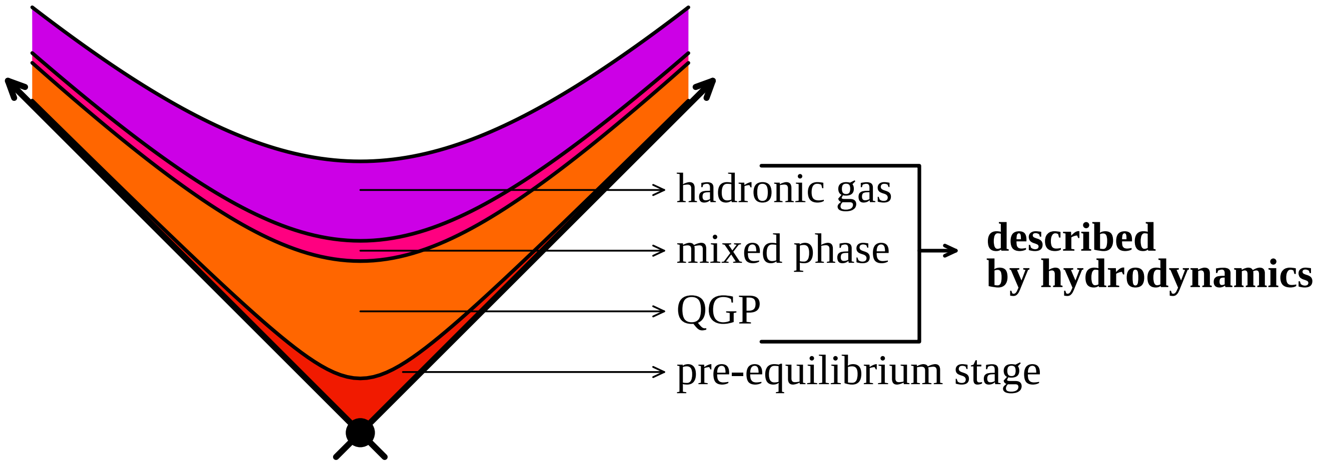
$$\frac{\partial N}{\partial \Phi} \propto 1 + 2\ v_2 \cos 2\Phi$$



Luzum, Romatschke (2008)

QGP and Relativistic Hydrodynamics

L.D.Landau (1953) *vs.* J.D.Bjorken (1982)



- Kinematic Landscape

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

- Energy-Momentum tensor (perfect fluid)

$$T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p\eta^{\mu\nu} \; ; \; u^\mu u^\mu = -1$$

- Hydrodynamics

$$\boxed{\partial_\mu T^{\mu\nu} = 0} \; ; \; \frac{\partial p}{\partial \epsilon} = c_s^2 (= 1/g) \; ; \; \boxed{T^{\mu\mu} = 0} \Rightarrow g = 3$$

Bjorken Flow (1)

Bjorken (1982)

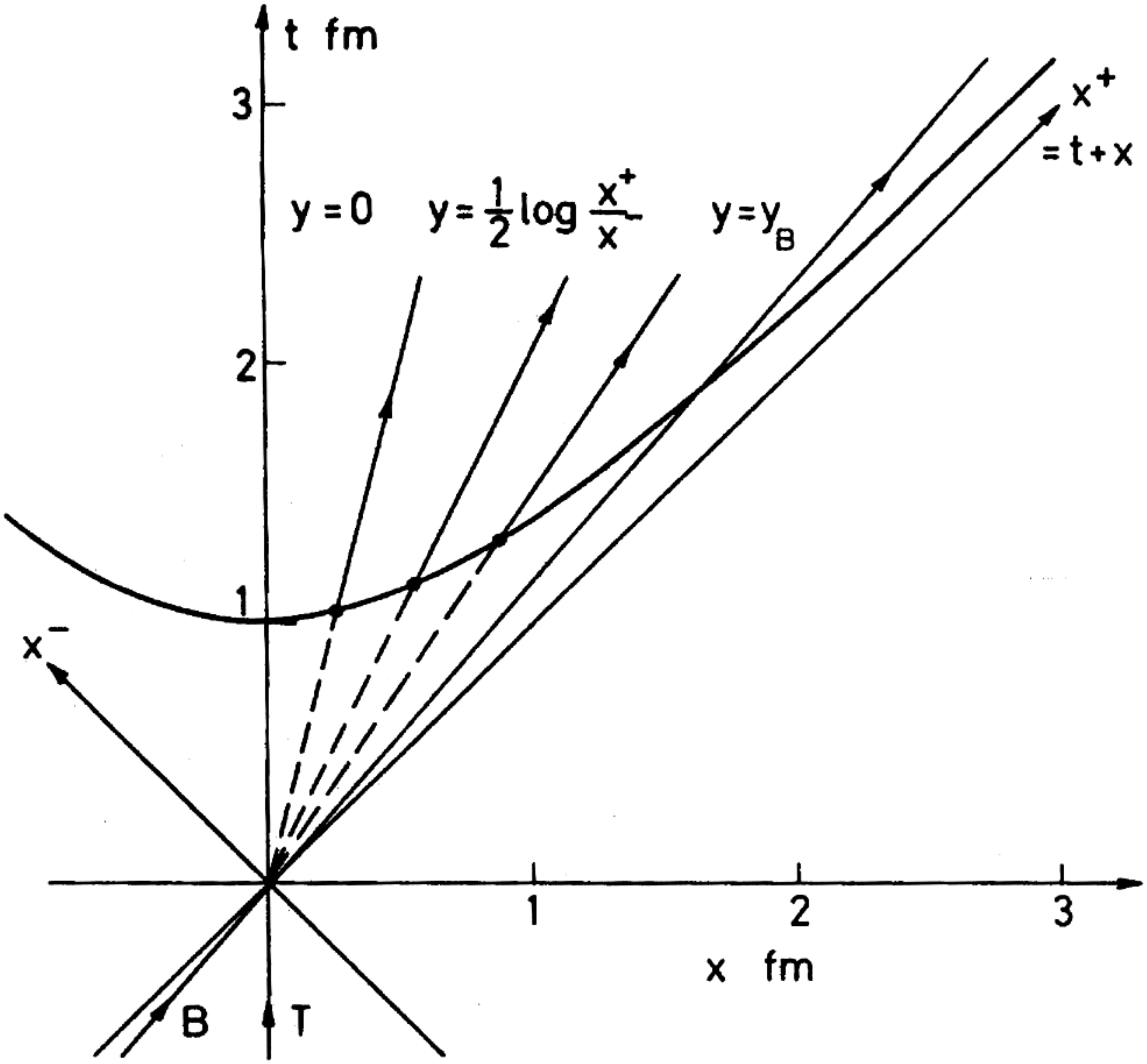


Fig.1

In-Out Ansatz

Bjorken (1976), Low & Gottfried (1978)

Bjorken Flow (2)

"In-out Ansatz" $\Rightarrow$ Boost Invariance

- Hydrodynamic Equations in 1+1 d: $\boxed{u^{\pm} = e^{\pm y}}$

$$\begin{aligned} T^{00} &= p\left[\left(\frac{1+g}{2}\right)\cosh y + \left(\frac{g-1}{2}\right)\right] \\ T^{01} &= p\left(\frac{1+g}{2}\right)\sinh y \\ T^{11} &= p\left[\left(\frac{1+g}{2}\right)\cosh y - \left(\frac{g-1}{2}\right)\right] \end{aligned}$$

$$\boxed{2g\partial_{\pm}[\log p] = -(1+g)^2\partial_{\pm}y - (g^2-1)e^{\mp 2y}\partial_{\mp}y}$$

- Rapidity Consistency Condition

$$\boxed{\partial_-\partial_+ y = \frac{g^2-1}{4(1+g)^2}\ \left\{\partial_-\partial_-[e^{-2y}] - \partial_+\partial_+[e^{2y}]\right\}}$$

- In-out Ansatz $y = \eta \Rightarrow$ Boost Invariance

$$\boxed{y = \eta = \frac{1}{2}(\log z^+ - \log z^-) \Rightarrow\ \partial_{\pm}[\log p] = -\frac{1+g}{2g\ z^{\pm}} \Rightarrow p = p_0\ (z^+z^-)^{-(g+1)/2g}}$$

$$\boxed{T_{Liberation} = p^{1/(g+1)} = T_0\ (z^+z^-)^{-1/2g} = T_0\ \tau^{-1/g}}$$

Landau Flow

Landau (1953)

- Landau Full Stopping solution $(z_+, z_- \equiv e^{\zeta_+}, e^{-\zeta_-})$

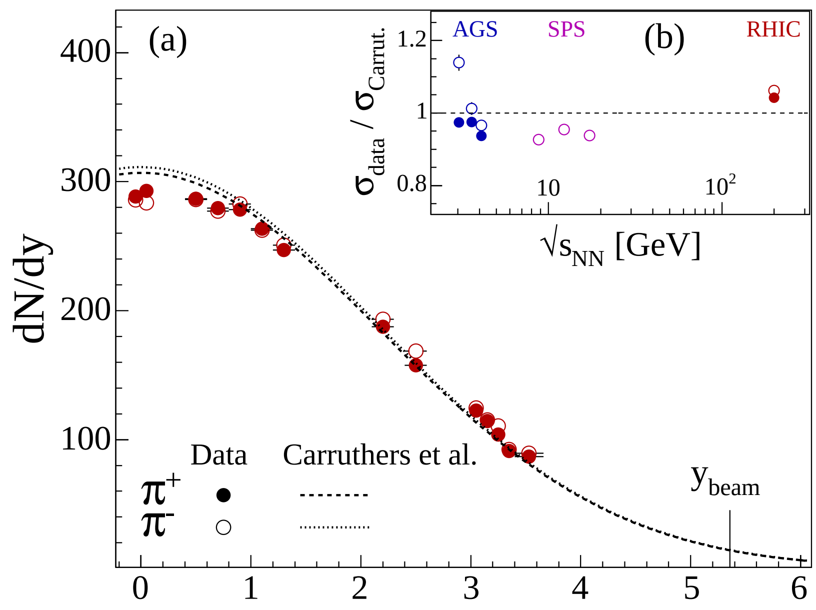
$$y \sim \frac{1}{2}\left(\left[\zeta_+ + \frac{1}{2}\log\zeta_+\right] - \left[\zeta_- + \frac{1}{2}\log\zeta_-\right]\right)$$

- Entropy Spectrum
  "Liberation" : $1{+}1 \rightarrow 3{+}1$ at $\tau = \sqrt{z_+ z_-} \sim e^{-Y/2}$

Landau (1953), Carruthers & Doung-van (1973)

$$dS \propto \exp -\frac{1}{2}\left(\zeta_+ + \zeta_- - 2\sqrt{\zeta_+\zeta_-}\right)\,dy \Rightarrow \frac{dS}{S\,dy} \sim \frac{dN}{N\,dy} \sim \frac{\exp -y^2/Y}{\sqrt{2\pi Y}}$$

- Brahms Results (2005)



Harmonic Flows

A.Bialas, R.A.Janik, R.P., 2007

- Generalized "In-Out Ansatz"

$$y = \tfrac{1}{2}\left[l_+^2(z^+) - l_-^2(z^-)\right]$$

- Rapidity Consistency Condition

$$\partial_-\partial_+ y \equiv 0 \Rightarrow \partial_-\partial_-[e^{-2y}] = \partial_+\partial_+[e^{+2y}]$$

- One-parameter family of Solutions (with given $g = c_s^{-2}$)

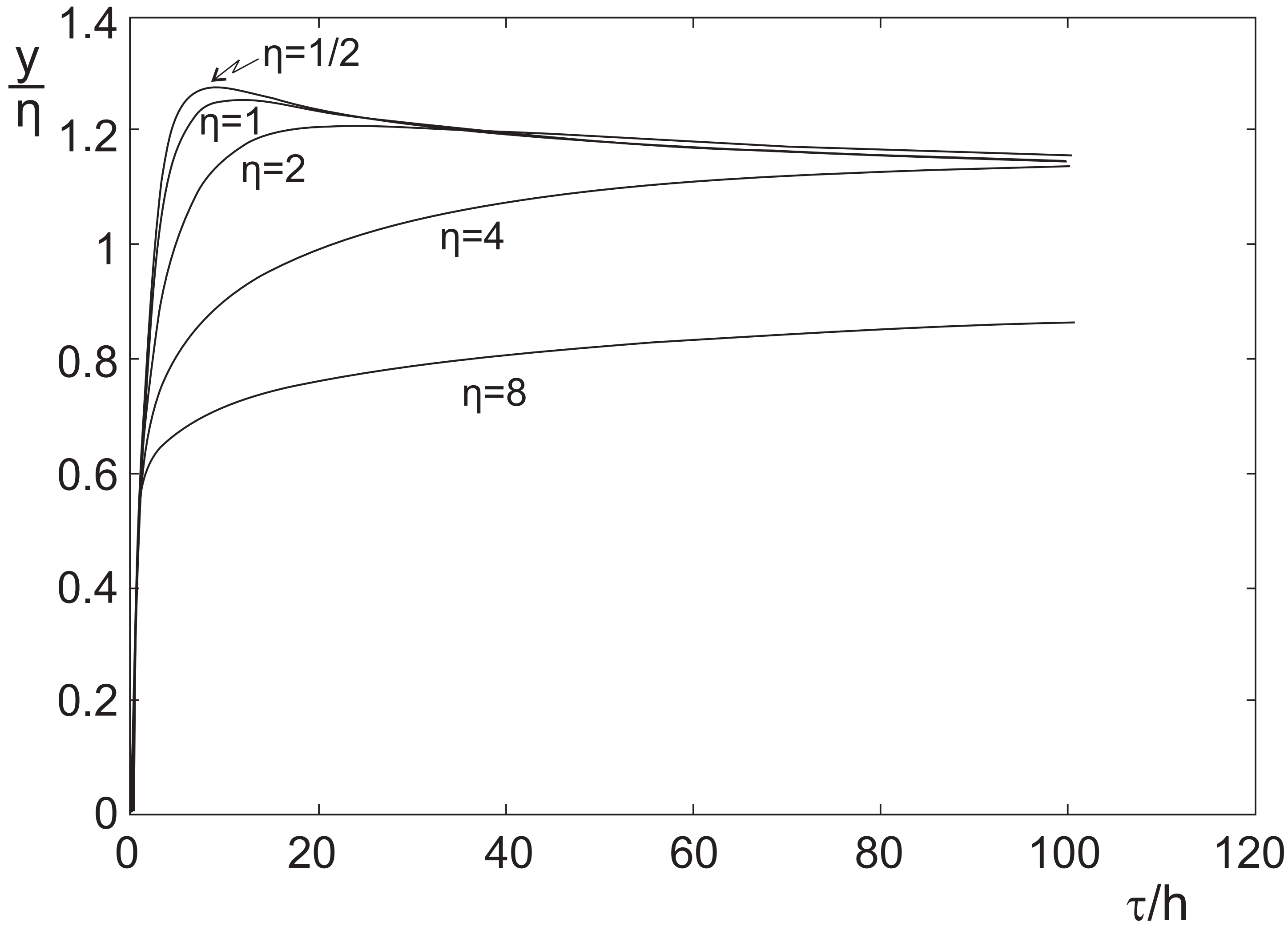
$$z_\pm = h \int_{l_0}^{l_\pm} e^{l^2}\, dl$$

$$p(z_+, z_-) = p_0 \exp\left\{-\frac{(1+g)^2}{4g}\left[l_+^2 + l_-^2\right] + \frac{g^2-1}{2g}\, l_+ l_-\right\}$$

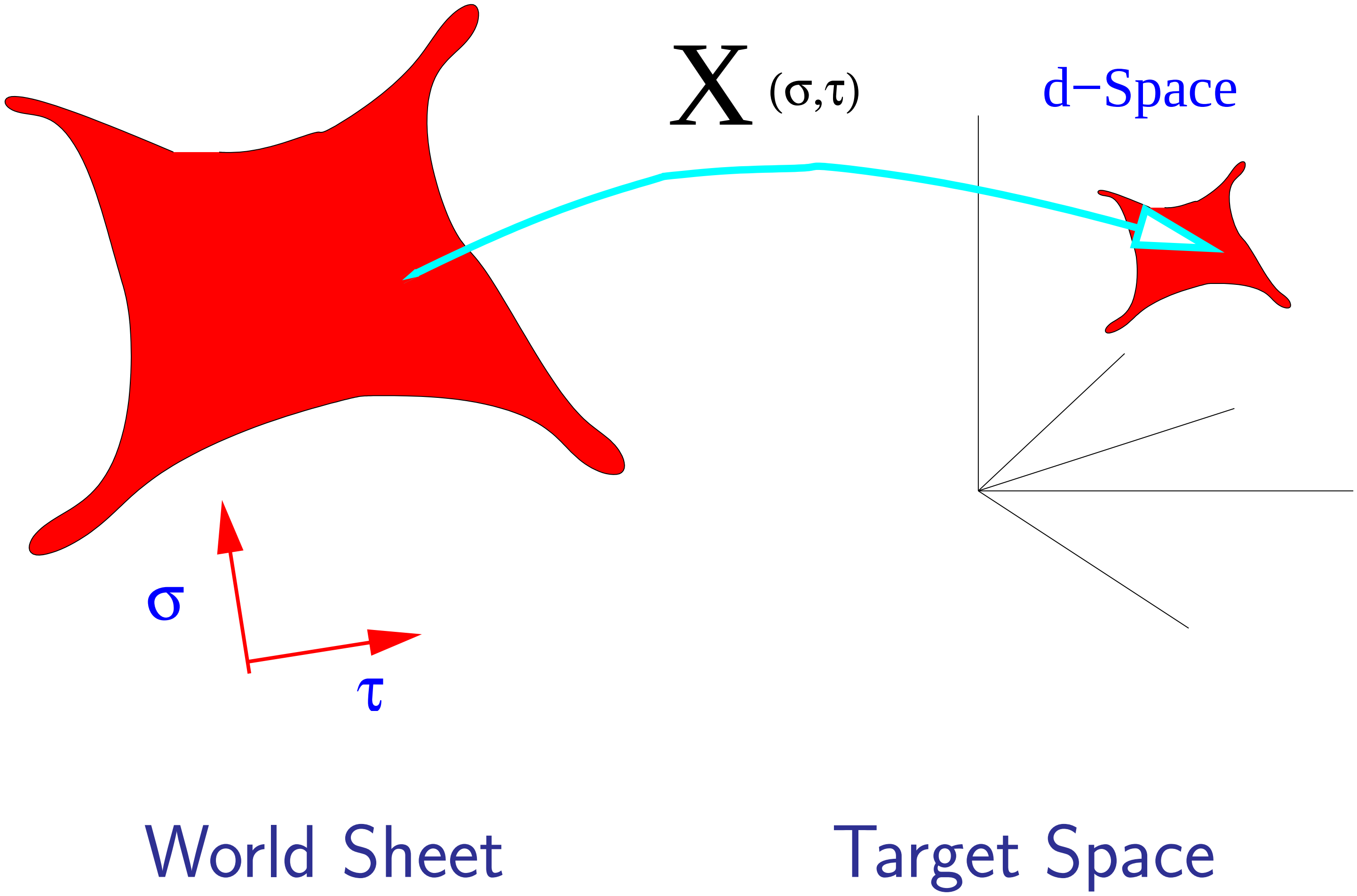
- Unification of L. and Bj. frameworks

Bjorken limit: $h \to 0,\ z_\pm\ fixed$; Landau limit: $h\ fixed,\ l_\pm \to \infty$

Full Stopping

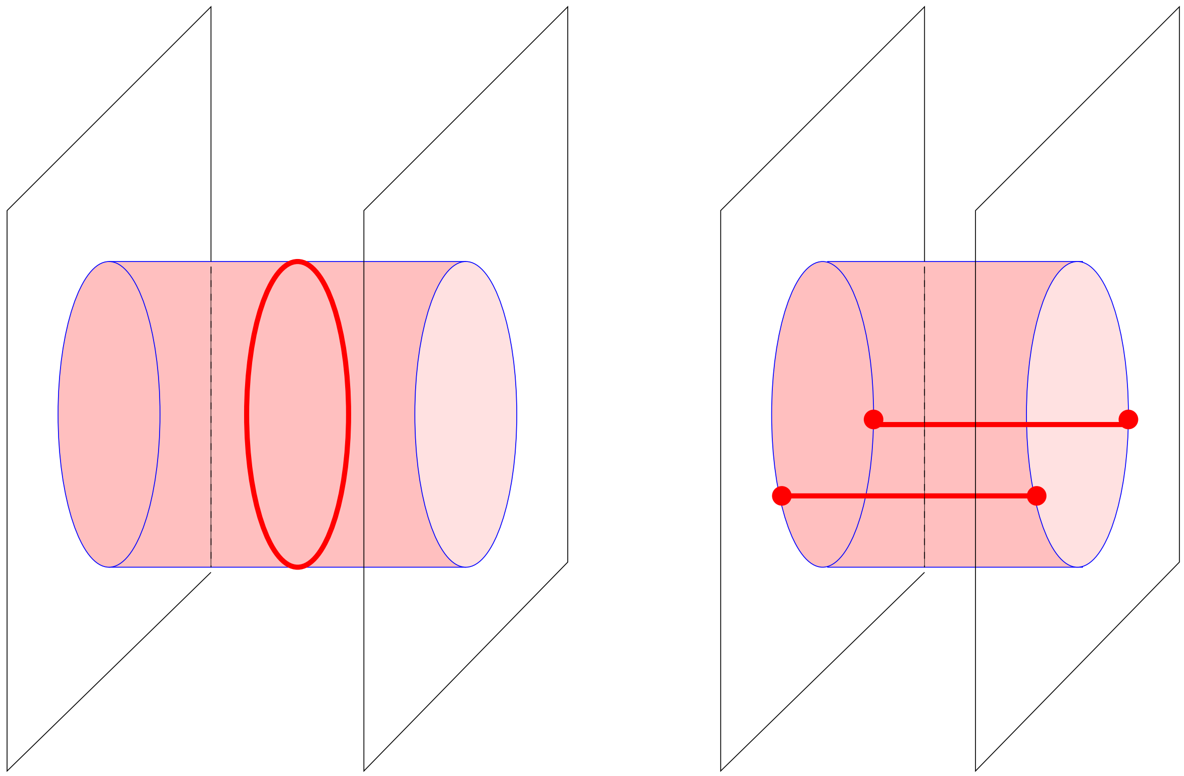


String Apparatus



The Gauge-Gravity Correspondence

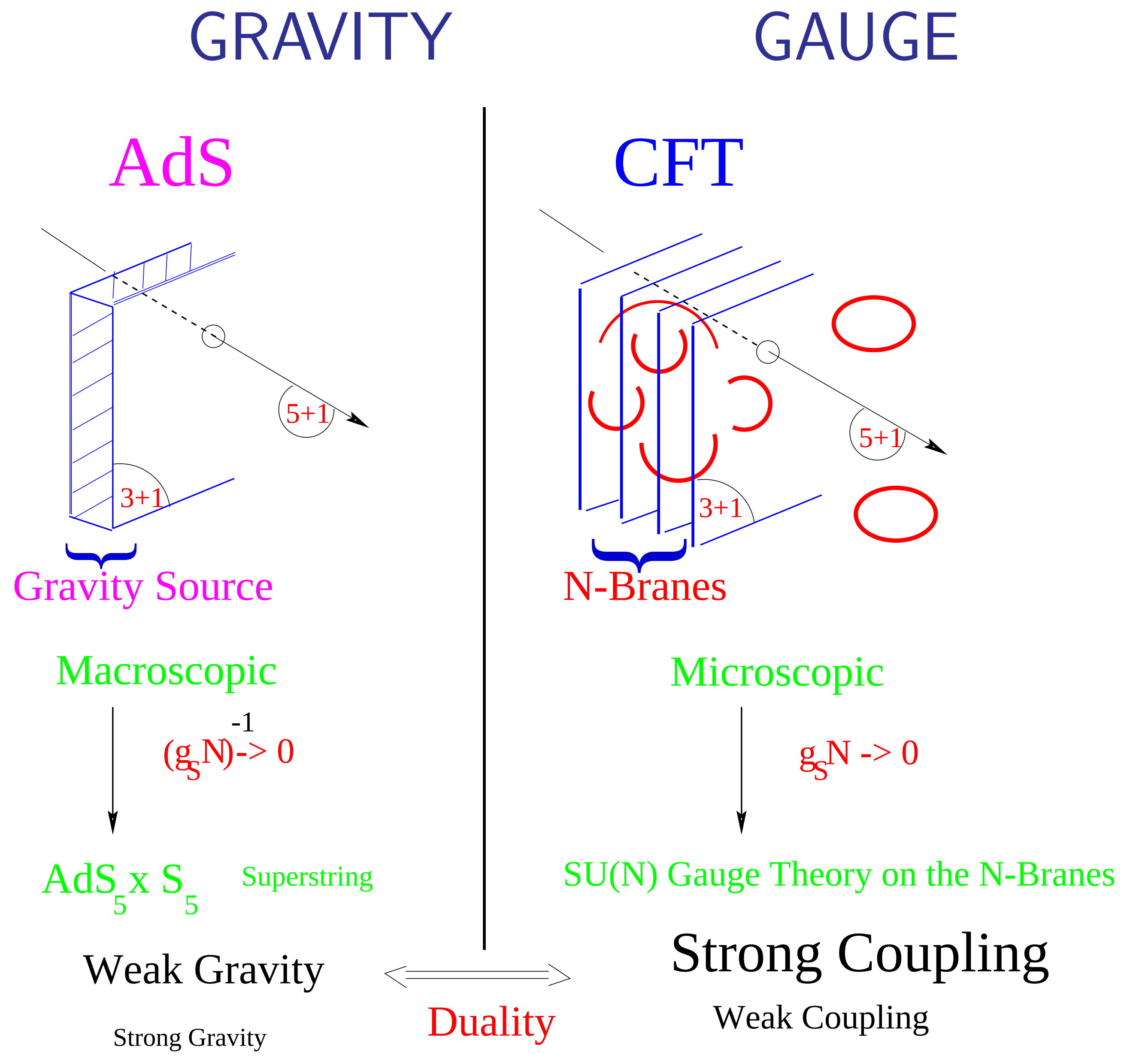
Open ⇔ Closed String duality



$$\begin{aligned} Closed\ String &\Leftrightarrow 1\!-\!loop\ Open\ String \\ Gravity &\Leftrightarrow Gauge \\ D\!-\!Brane\ \text{“}Universe\text{''} &\Rightarrow Open\ String\ Ending \\ Small/Large\ Distance &\Rightarrow Gauge/Gravity\ Correspondence \end{aligned}$$

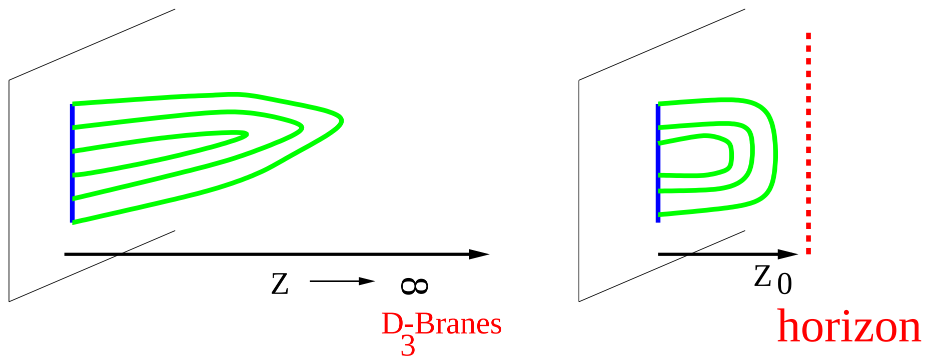
AdS/CFT Correspondence

J.Maldacena (1998)



Holography at work

- Holographic Principle: Brane/Bulk correspondence



$\boxed{\mathrm{Non-Confining}}$ Confining Geometry

- Brane → Bulk: Holographic Renormalization

K.Skenderis (2002)

$$\boxed{ds^2 = \frac{g_{\mu\nu}dx^\mu dx^\nu + dz^2}{z^2}}$$

(in Fefferman-Graham Coordinates)

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

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

Perfect Fluid $\Leftrightarrow$ 5d Black Hole (static case)

Balasubramanian,de Boer,Minic; Myers

- Perfect Fluid $\Rightarrow$ 5d Black Hole

from (resummed) Holographic Renormalisation (Janik,R.P.)

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

- Derivation of the Fefferman-Graham metrics

$$ds^2 = -\frac{(1 - z^4/z_0^4)^2}{(1 + z^4/z_0^4)z^2} dt^2 + (1 + z^4/z_0^4)\frac{dx^2}{z^2} + \frac{dz^2}{z^2}$$

- It is indeed the $5-d$ Black Brane with horizon at $\tilde{z}_0$

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

$Z \rightarrow \tilde{Z} = Z \cdot \left\{1 + Z^4/Z_0^4\right\}^{-1/2}$

Other features (static case)

- Temperature and entropy

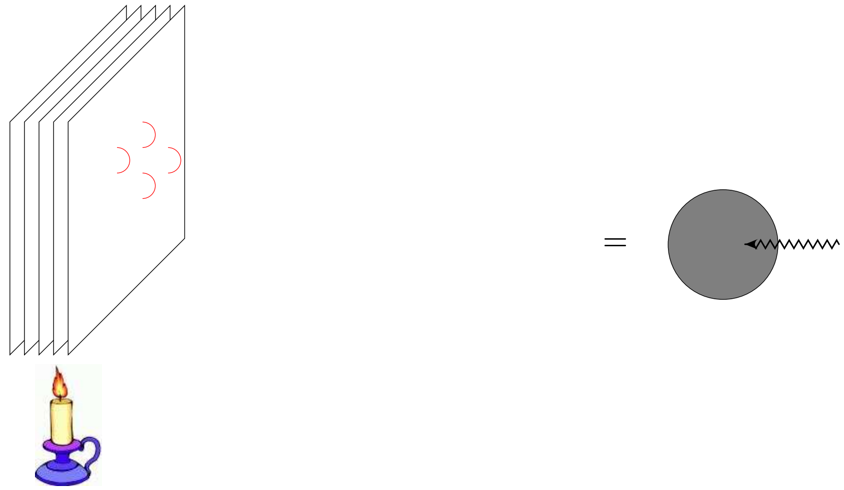
$$\textit{Temperature}: \; T_{BlackHole} = \sim \frac{1}{\tilde{z}_0} = \epsilon^{\frac{1}{4}} = T_{PerfectFluid}$$

$$\textit{Entropy}: \; S_{BlackHole} \sim Area = \frac{1}{\tilde{z}_0^3} \sim \epsilon^{\frac{3}{4}} = S_{PerfectFluid}$$

- Viscosity (Policastro, Son, Starinets, 2001)

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:

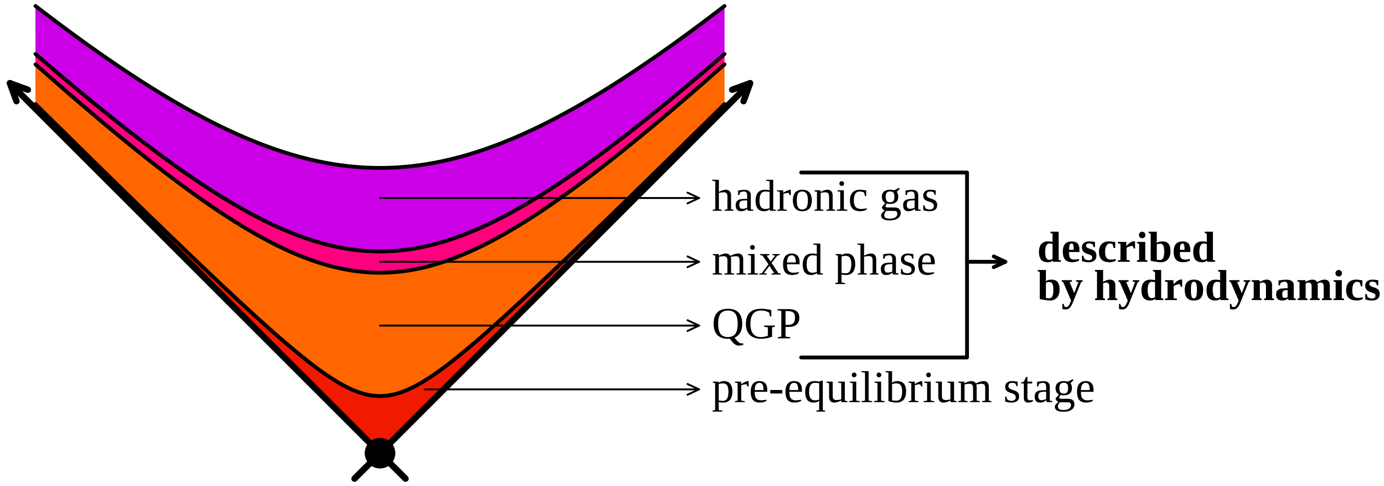


Absorption by D3 branes ($\sim$ viscosity) = absorption by black hole

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

Gauge/Gravity: From Statics to Dynamics

R.Janik, R.P. (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)): Construct the Dual ?
- QGP: (almost) Perfect fluid behaviour, why?
- Universal $\frac{\eta}{S}$?
- Fast Pre-equilibrium stage, why?

4d-Hydrodynamics

- Energy-Momentum Tensor

$$T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - p\eta^{\mu\nu}$$

- Relativistic Hydrodynamic Equations

$\partial_\mu T^{\mu\nu} = 0 :$ Continuity condition

$T^{\mu\mu} = 0 :$ Traceless condition

$\epsilon = p c_{sound}^{-2} :$ Equation of State

- Thermodynamical Identities

$$p + \epsilon = \epsilon\ (1 + c_s^2) = TS\ ; \quad d\epsilon = TdS$$

$$\epsilon = p\ c_s^{-2} = \epsilon_0 T^{(1+c^2)/c^2}\ ; \quad S = S_0\ T^{1/c^2} \ \rightarrow \ S \sim \epsilon^{1/(c^2+1)}$$

AdS/CFT *implies* Perfect Fluid at large τ

- Family of Boost-invariant T^{μ}_{ν}

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

- Proper-time evolution

$$\boxed{f(\tau) \propto \tau^{-s}}$$

$$T_{\mu\nu} t^{\mu} t^{\nu} \geq 0 \Rightarrow 0 < s < 4$$

$f(\tau) \propto \tau^{-\frac{4}{3}}$: Perfect Fluid $\epsilon = 3p_{\perp} = 3p_L$

$f(\tau) \propto \tau^{-1}$: Free streaming $\epsilon = 2p_{\perp};\ p_L = 0$

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

Expanding Geometries

- General Boost-Invariant F-G metric:

$$ds^2 = \frac{-e^{a(\tau,z)}\ d\tau^2 + \tau^2 e^{b(\tau,z)}\ dy^2 + e^{c(\tau,z)}\ dx_\perp^2}{z^2} + \frac{dz^2}{z^2}$$

- Einstein Equation(s):

$$\{a(\tau,z), b(\tau,z), c(\tau,z)\} = \{a(v), b(v), c(v)\} + \mathcal{O}\left(\frac{1}{\tau^\#}\right)$$

$$\text{Asymptotic Scaling} \quad \Rightarrow \quad v = \frac{z}{\tau^{s/4}}$$

$$v(2a'(v)c'(v)+a'(v)b'(v)+2b'(v)c'(v))-6a'(v)-6b'(v)-12c'(v)+vc'(v)^2 = 0$$

$$3vc'(v)^2+vb'(v)^2+2vb''(v)+4vc''(v)-6b'(v)-12c'(v)+2vb'(v)c'(v) = 0$$

$$2vsb''(v) + 2sb'(v) + 8a'(v) - vsa'(v)b'(v) - 8b'(v) + vsb'(v)^2 + 4vsc''(v) + 4sc'(v) - 2vsa'(v)c'(v) + 2vsc'(v)^2 = 0 \ .$$

- Asymptotic Solution

$$\begin{aligned} a(v) &= A(v) - 2m(v) \\ b(v) &= A(v) + (2s-2)m(v) \\ c(v) &= A(v) + (2-s)m(v) \end{aligned}$$

$$A(v)=\frac{1}{2}\left(\log(1+\Delta(s)\,v^4)+\log(1-\Delta(s)\,v^4)\right) \quad m(v)=\frac{1}{4\Delta(s)}\left(\log(1+\Delta(s)\,v^4)-\log(1-\Delta(s)\,v^4)\right. \quad \Delta(s)=\sqrt{3s^2-8s+8/24}$$

General Scaling Solution

$$v = \frac{z}{\tau^{s/4}}$$

- Exemple: Asymptotic metric for Free Streaming

$$z^2\ ds^2 = \Bigg(-(1+\tfrac{v^4}{\sqrt{8}})^{\frac{1-2\sqrt{2}}{2}}(1-\tfrac{v^4}{\sqrt{8}})^{\frac{1+2\sqrt{2}}{2}}dt^2+(1+\tfrac{v^4}{\sqrt{8}})^{\frac{1}{2}}(1-\tfrac{v^4}{\sqrt{8}})^{\frac{1}{2}}\tau^2 dy^2 +$$

$$+(1+\tfrac{v^4}{\sqrt{8}})^{\frac{1+\sqrt{2}}{2}}(1-\tfrac{v^4}{\sqrt{8}})^{\frac{1-\sqrt{2}}{2}}dx_\perp^2 \Bigg) + \ dz^2$$

- Investigating the Geometry:

Ricci scalar:

$$R = -20 + \mathcal{O}\left(\frac{1}{\tau^{\#}}\right)$$

Riemann tensor squared:

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

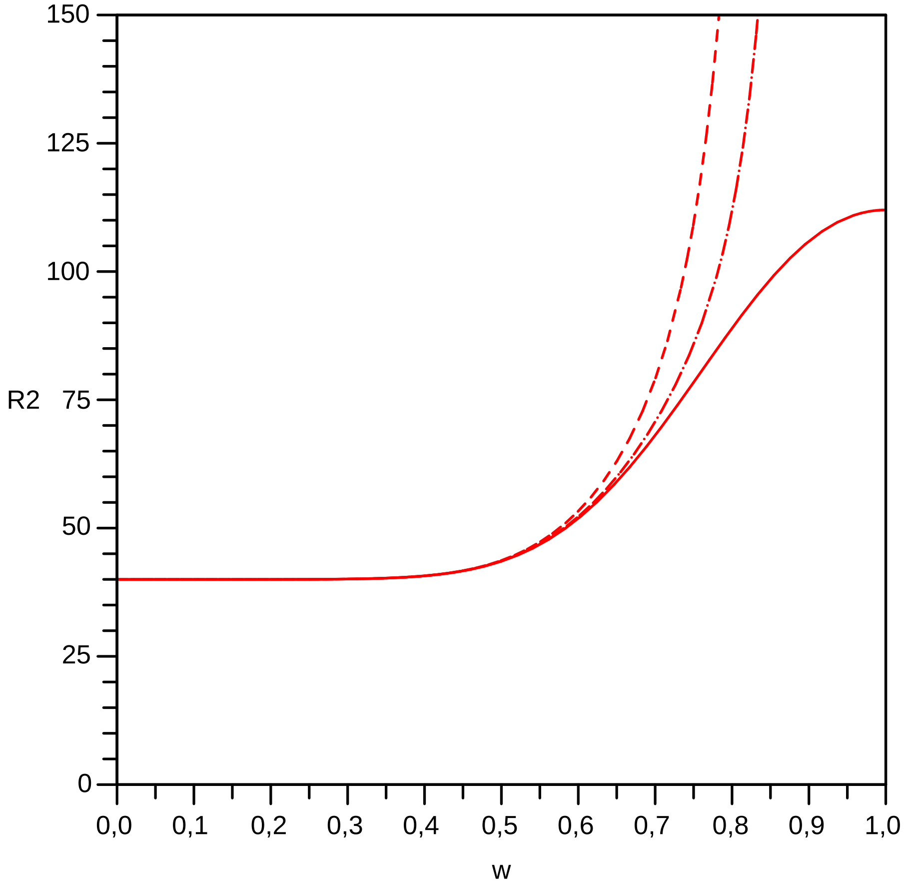
General Curvature invariant

$$\boxed{\mathfrak{R}^2 = R^{\mu\nu\alpha\beta} R_{\mu\nu\alpha\beta}}$$

$$\mathfrak{R}^2 = \frac{4}{\left(1 - \Delta(s)^2 v^8\right)^4} \cdot \Big[10\,\Delta(s)^8 v^{32} - 88\,\Delta(s)^6 v^{24} + 42\,v^{24} s^2 \Delta(s)^4 +$$
$$+112\,v^{24}\Delta(s)^4 - 112\,v^{24}\Delta(s)^4 s + 36\,v^{20} s^3 \Delta(s)^2 - 72\,v^{20} s^2 \Delta(s)^2 +$$
$$+828\,\Delta(s)^4 v^{16} + 288\,v^{16}\Delta(s)^2 s - 288\,v^{16}\Delta(s)^2 - 108\,v^{16} s^2 \Delta(s)^2 +$$
$$-136\,v^{16} s^3 + 27\,v^{16} s^4 - 320\,v^{16} s + 160\,v^{16} + 296\,v^{16} s^2 + 36\,v^{12} s^3 +$$
$$-72\,v^{12} s^2 - 88\,\Delta(s)^2 v^8 + 42\,v^8 s^2 + 112\,v^8 - 112\,v^8 s + 10\Big] + \mathcal{O}\left(\frac{1}{\tau^{\#}}\right)$$

AdS/CFT: Selection of the Perfect Fluid

Singular Scalar $\mathfrak{R}^2$ for $s = \frac{4}{3} \pm .1$



Regular Scalar $\mathfrak{R}^2$ for $s = \frac{4}{3}$:

$$\mathfrak{R}^2{}_{\text{perfect fluid}} = \frac{8(5w^{16} + 20w^{12} + 174w^8 + 20w^4 + 5)}{(1 + w^4)^4}$$

$$w = v/\Delta(\tfrac{4}{3})^{\frac{1}{4}} \equiv \sqrt[4]{3}\, v.$$

Moving Black Hole Dual of a Perfect Relativistic fluid

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

- Asymptotic (Fefferman-Graham) metric

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

- Interpretation: Black Hole moving off in the 5th dimension (in FF-G coordinates)

$$Horizon:\ z_0 = (3/e_0)^{\frac{1}{4}}\cdot\tau^{\frac{1}{3}}$$

$$Temperature:\ T(\tau)\sim 1/z_0 \sim \tau^{-\frac{1}{3}}$$

$$Entropy:\ S(\tau)\sim Area \sim \tau\cdot 1/z_0^3 \sim const$$

- In $1 \longrightarrow 1$ correspondence with Bjorken flow

In-flow Viscosity and Relaxation time

R.Janik, R.Janik and M.Heller;

- Shear Viscosity equation (first order)

$$\boxed{\partial_\tau \epsilon = -\frac{4}{3}\frac{\epsilon}{\tau} + \frac{\eta}{\tau^2}}$$

- Asymptotic Expansion of the Black Hole Solution

$$\boxed{a(\tau,z), b(\tau,z), c(\tau,z) \Rightarrow \sum_n \lambda_n^{a,b,c}(v)\ \tau^{-2n/3}}$$

$$\mathfrak{R}^2 = R^{\mu\nu\alpha\beta} R_{\mu\nu\alpha\beta} \Rightarrow \sum_n \mathfrak{R}^2{}_n\ \tau^{-2n/3}$$

- Results

$\boxed{\frac{\eta}{S} = \frac{1}{4\pi}}$ Universality (needs $n \to 2$)

$\boxed{\tau_{Rel} = (1 - \log 2)/(2\pi T)}$ Relaxation Time: $n \to 3$

R. Baier, P. Romatschke, D.T. Son, A.O. Starinets, M.A. Stephanov;

M. Natsuume, T. Okamura

$\boxed{\langle \mathrm{Tr} F^2 \rangle < 0 :}$ Einstein+Dilaton; Magnetic > Electric

Isotropization/Thermalization (1)

R.Janik,R.P.

Stability of the expanding plasma

- Quasinormal scalar modes

$$\Delta\phi \equiv \frac{1}{\sqrt{-g}}\partial_n\left(\sqrt{-g}g^{ij}\partial_j\phi\right) = 0$$

$$-\frac{1}{v^3}\frac{(1+v^4)^2}{1-v^4}\partial_\tau^2\phi(\tau,v) + \tau^{-\frac{2}{3}}\ \partial_v\left(\frac{1}{v^3}(1-v^8)\partial_v\phi(\tau,v)\right) = 0$$

- Separation of variables $\phi(\tau,v) = f(\tau)\phi(v)$

$$\partial_\tau^2 f(\tau) = -\omega^2\tau^{-\frac{2}{3}}f(\tau) \ \Rightarrow\ f(\tau) = \sqrt{\tau}J_{\pm\frac{3}{4}}\left(\frac{3}{2}\omega\tau^{\frac{2}{3}}\right)\ \sim\ \tau^{\frac{1}{6}}\ e^{\frac{3}{2}i\omega\tau^{\frac{2}{3}}}$$

$$\partial_v\left(\frac{1}{v^3}(1-v^8)\partial_v\phi(v)\right) + \omega^2\frac{1}{v^3}\frac{(1+v^4)^2}{1-v^4}\phi(v) = 0$$

$\sim$ G. T. Horowitz and V. E. Hubeny (1999)

- Short Decay Proper-Time

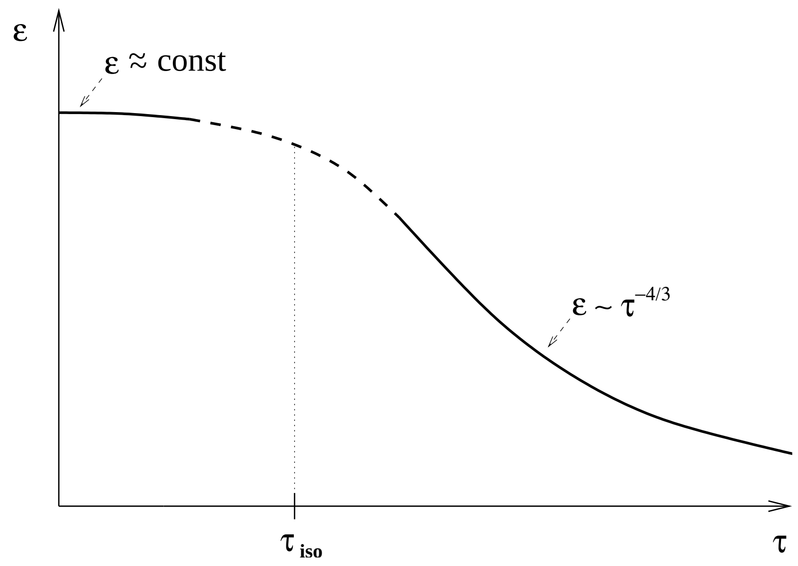
$$\frac{\omega_c}{\pi T} \sim 3.1194 - 2.74667\ i \Rightarrow \tau \sim \frac{1}{8.3\ T}$$

Isotropization/Thermalization (2)

Kovchegov, Taliotis

Evolution at small *vs.* large proper-time

Assuming Monodromy instead of Regularity



Evaluation of The Isotropization/Thermalization time

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

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

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

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

Initial Conditions: Shock Waves (1)

- One Initial Shock Wave

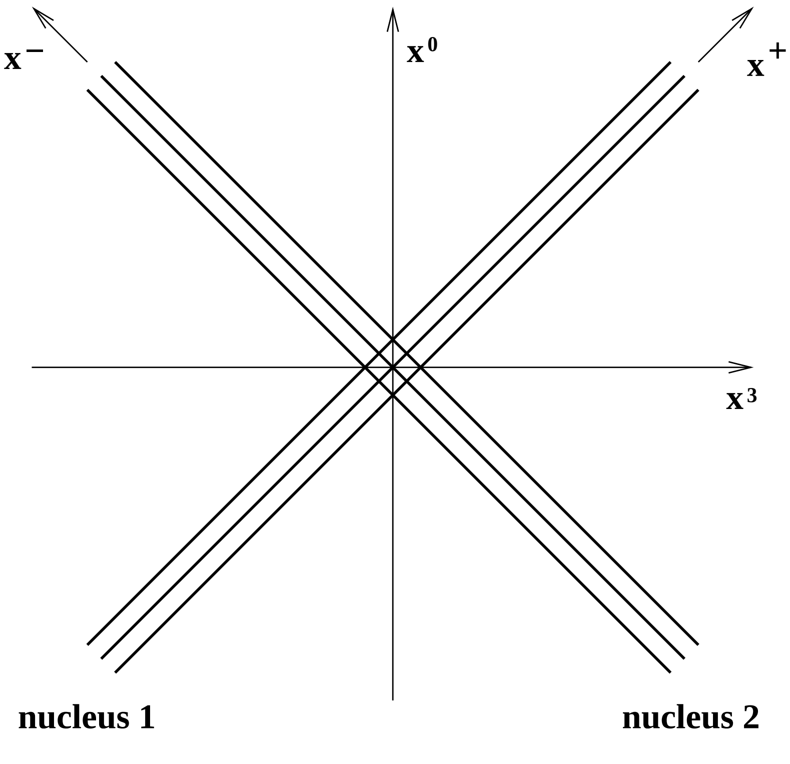
Janik,R.P.(2005)

$$ds^2 = \frac{-2dx^+dx^- + \mu_1 z^4 \delta(x^-) dx^{-2} + d\mathbf{x}_\perp{}^2 + dz^2}{z^2}$$

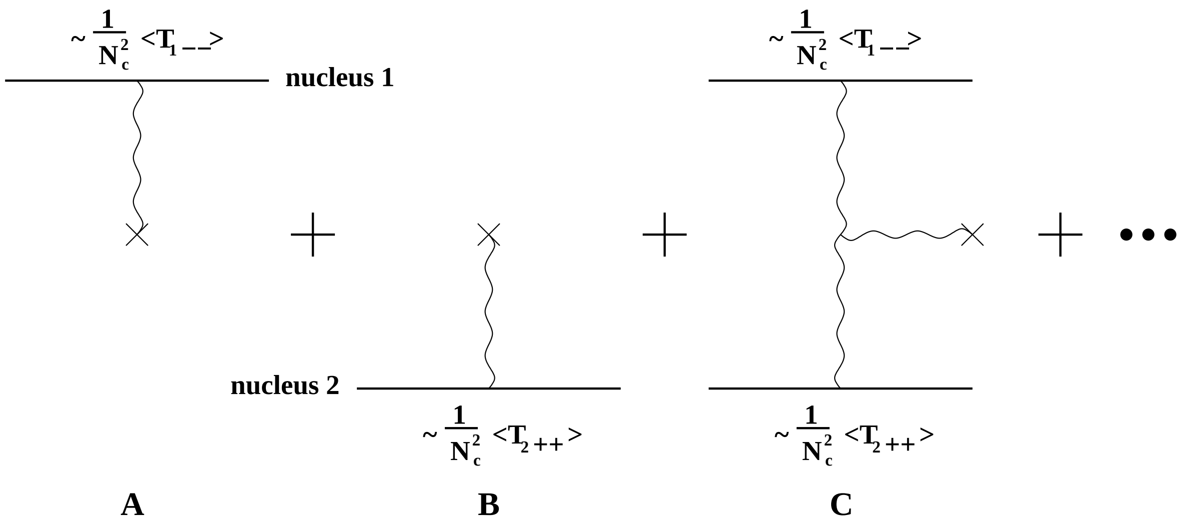
- Shock-wave collisions

Grumiller,Romatschke (2008)

Albacete,Kovchegov,Taliotis (2008)



Initial Conditions: Shock Waves (2)

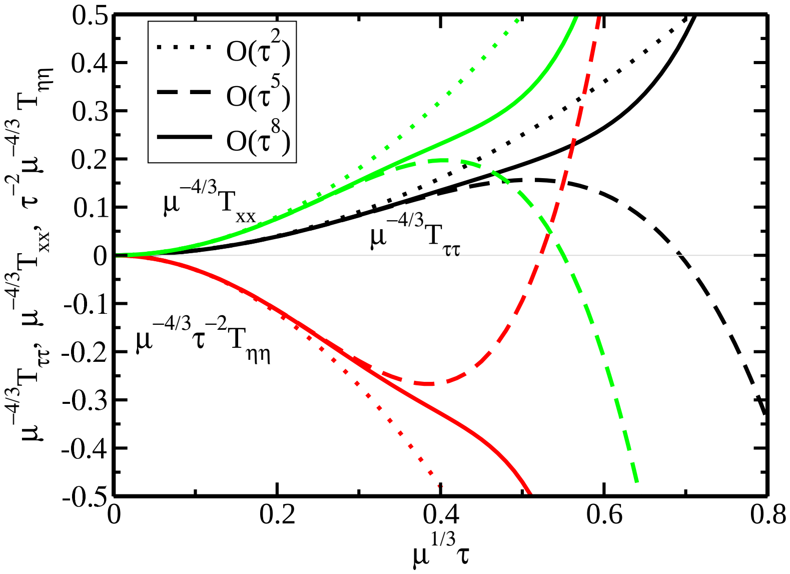


$$ds^2 = \frac{L^2}{z^2}\left\{ -2\,dx^+\,dx^- + dx_\perp^2 + dz^2 + \frac{2\,\pi^2}{N_c^2}\,\langle T_{1\,--}(x^-)\rangle\,z^4\,dx^{-\,2} + \frac{2\,\pi^2}{N_c^2}\,\langle T_{2\,++}(x^+)\rangle\,z^4\,dx^{+\,2} + \text{higher order graviton exchanges}\right\} \quad (1)$$

From: Albacete, Kovchegov, Taliotis

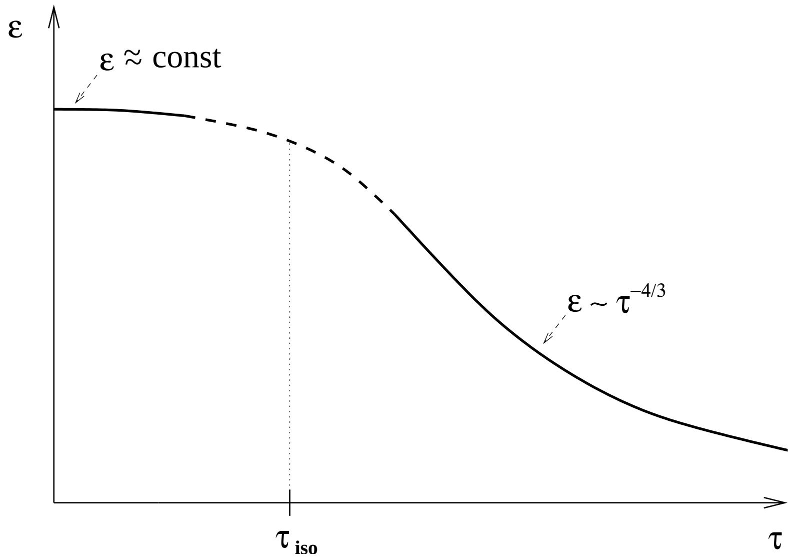
Initial Conditions: Shock Waves (3)

- Strong Coupling: Full Stopping $\sim$ Landau



From: Grumiller, Romatschke

- Weak Coupling



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, Thermalization, Flavors, Instabilities
- NB: Other studies
  Jet Quenching, Quark Dragging, ...

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?

Why Eintein Eqs. govern the strong coupling $\mathcal{N}^4$QGP?

EXTRA SLIDES

More on AdS$_5$

- D_3-brane Solution of Super Gravity:

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

"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

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

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

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