Gauge-gravity duality and high-energy collisions

Robi Peschanski
(IPhT, Saclay)
New Trends in HERA Physics 2008
Ringberg Castle, Tegernsee

- Gauge/Gravity correspondence and AdS/CFT

  An Introduction

- Gravity dual of an expanding medium

  A medium: Hydrodynamics and the sQGP

- Gravity dual of a high-energy collision

  Scattering at strong gauge coupling

- Prospects on QCD & AdS/CFT (tentative)

  A growing subject

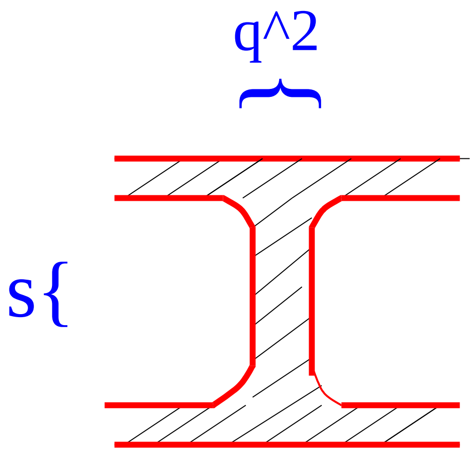
Strong Interactions and Strings

Historical Remark

Strings $\not\Leftrightarrow$ QCD $\Leftrightarrow$ Strings

$\boxed{1968} \Rightarrow \boxed{1974} \Rightarrow \boxed{1998} \Rightarrow \boxed{2008} \ldots$

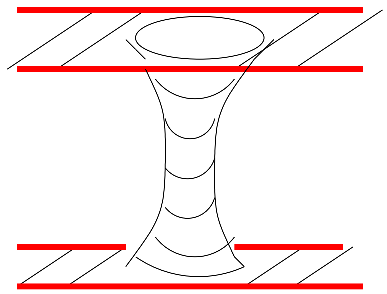
Open String	*Closed String*



Veneziano Amplitude

$A_R(s,q^2)$

Gauge



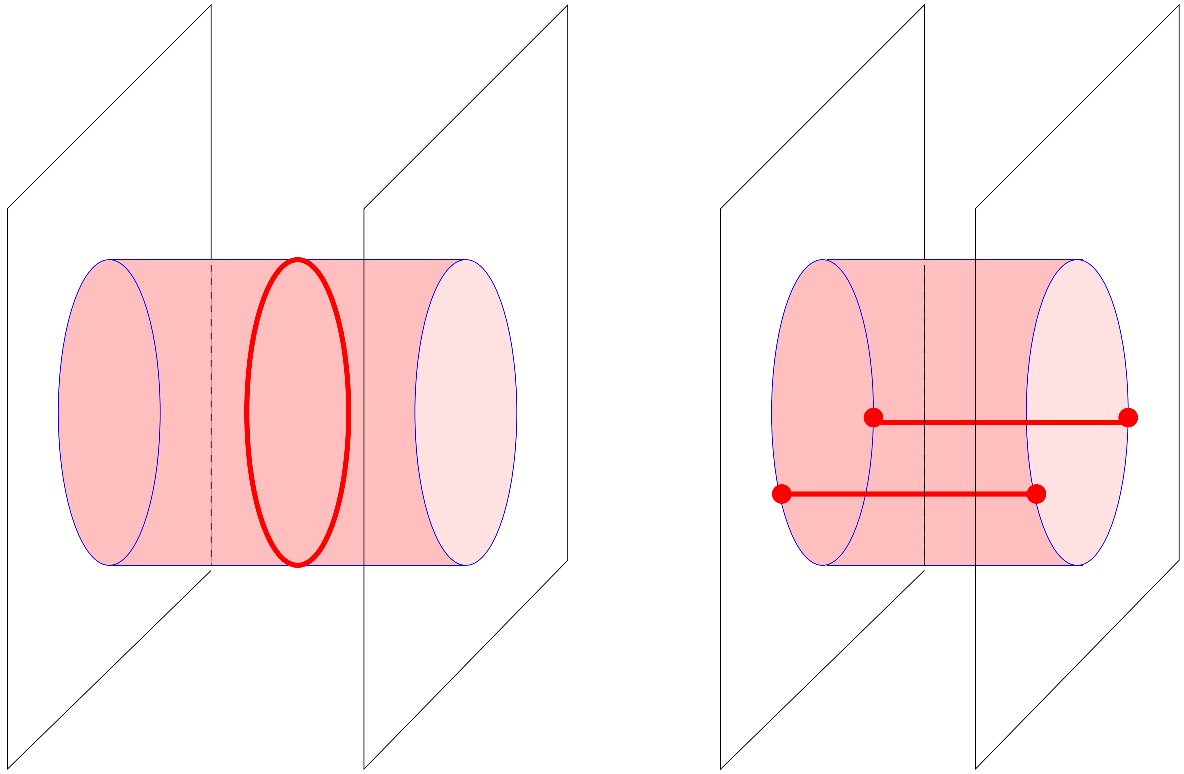
Shapiro-Virasoro Amplitude

$A_P(s,q^2)$

Gravity

The Gauge-Gravity Correspondence

"Duality": Open String $\Leftrightarrow$ Closed String

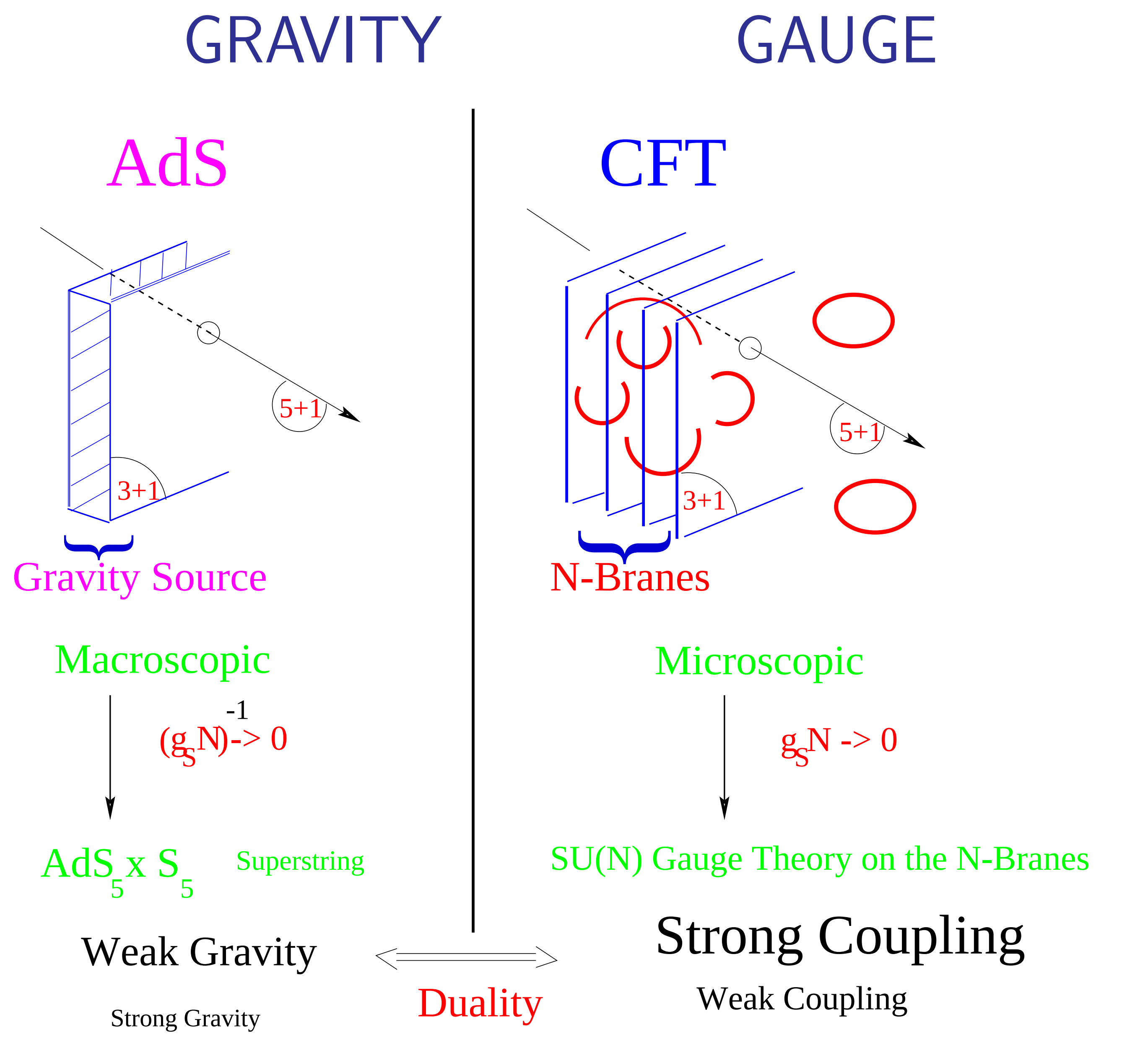


Schomerus, 2006

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

AdS/CFT Correspondence

J.Maldacena (1998)



WHY AdS$_5 \otimes S_5$?

- Solution of Gravity for D_3 Branes: Horowitz,Strominger, 1991

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

"Physical" Branes (d=1+3) + Extra-Dimensions (d=6)

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

- "Maldacena breakthrough": Maldacena, 1998

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

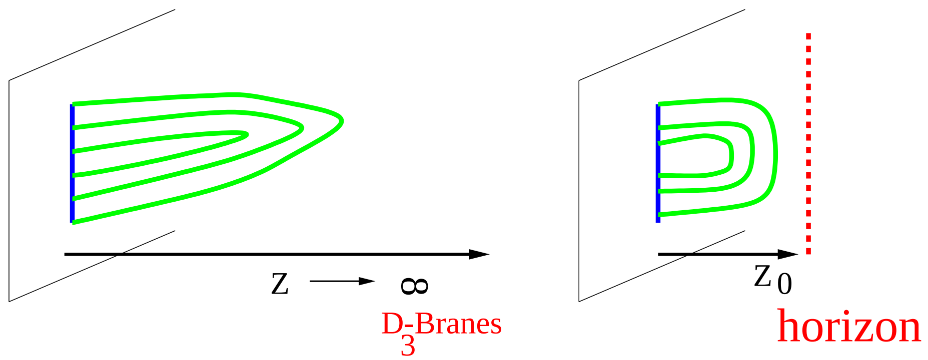
Strong coupling limit

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

Background Structure: AdS$_5 \otimes S_5$ (same R^2)

HOLOGRAPHY

- Holographic Principle: Brane/Bulk correspondence



$AdS_5 \otimes S_5$ $\qquad$ $Confining\ Geometry$

- Brane → Bulk: Holographic Renormalization

K.Skenderis (2002)

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

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

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

EMERGENCE of the 5d BLACK HOLE

Balasubramanian,de Boer,Minic (2002)

- 4d Perfect Fluid "on the brane"

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

- Holographic Renormalisation (Resummed) Janik,R.P. (2005)

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

- $\Rightarrow 5d$ Black Brane with horizon at $z_0 \sim T_0^{-3}$

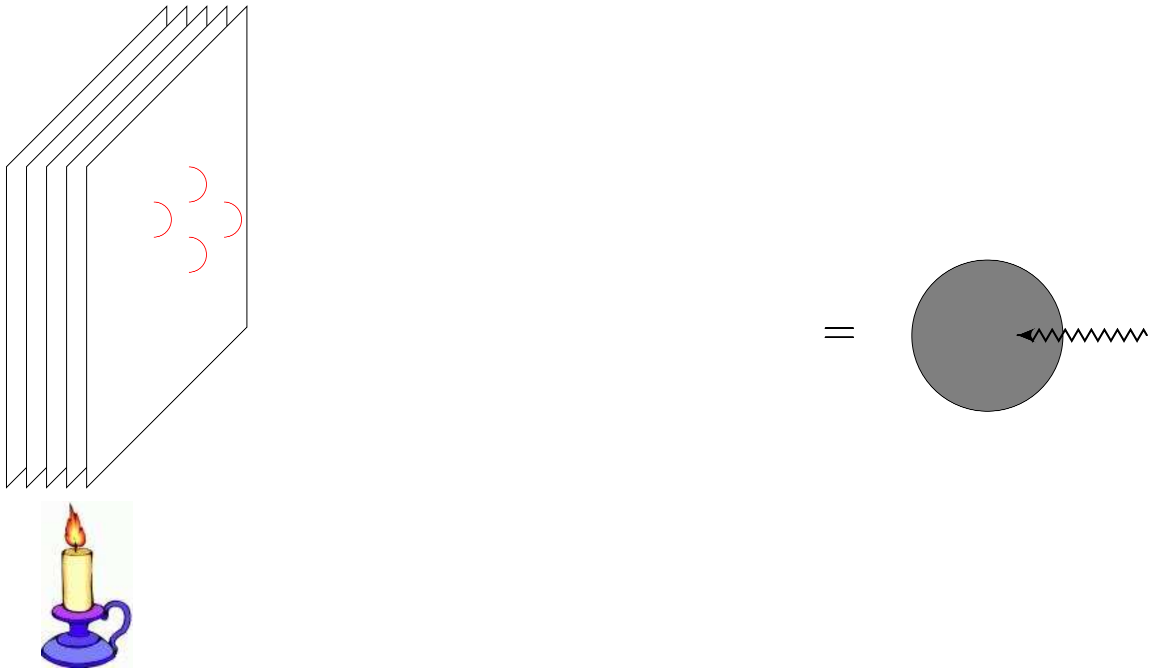
$$ds^2 = -\frac{1 - \tilde{z}^4/\tilde{z}_0^4}{\tilde{z}^2}dt^2 + \frac{dx^2}{\tilde{z}^2} + \frac{1}{1 - \tilde{z}^4/\tilde{z}_0^4}\frac{d\tilde{z}^2}{\tilde{z}^2}$$

$$z \longrightarrow \tilde{z} = z/\sqrt{1+\frac{z^4}{z_0^4}}$$

HYDRODYNAMICS $vs.$ GRAVITY

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:



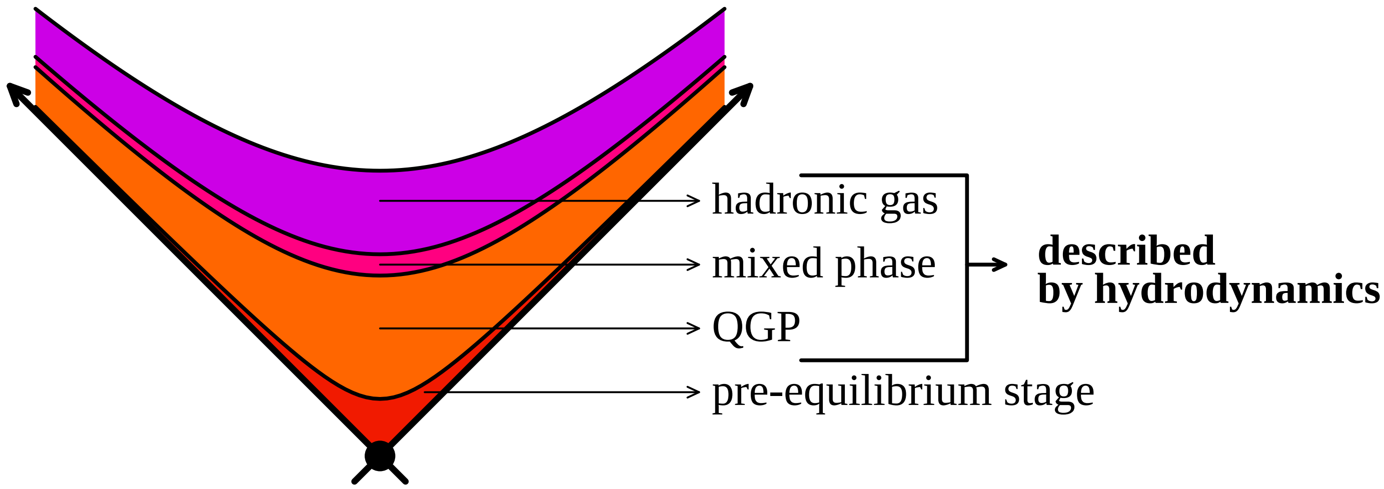
Absorption by D3 branes ($\sim$ viscosity) = absorption by black hole

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

Policastro, Son, Starinets (2001)

Gauge/Gravity: From QGP Statics to Dynamics

Janik, R.P.
Janik, Heller, Benincasa, Buchel...
Kovchegov, Taliotis, Albacete,...
Nakamura,Sin,Kinoshita, Mukoyama, Nakamura, Oda,Natsuume, Okamura,...
Bhattacharyya, Hubeny, Minwalla, Ranganami, Loganayagam,...
......,...



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

Questions

- What is the Gravity Dual of a Flow?
- QGP: (almost) Perfect fluid behaviour, why?
- Universal $\frac{\eta}{S}$, Transport coefficients, Navier-Stokes,...
- Fast Pre-equilibrium stage, why?

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

R.Janik, RP (2005)

- Boost-invariant T^{μ}_{ν} (Bjorken, 1983)

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

- 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 $\epsilon = p_{\perp} = -p_L$

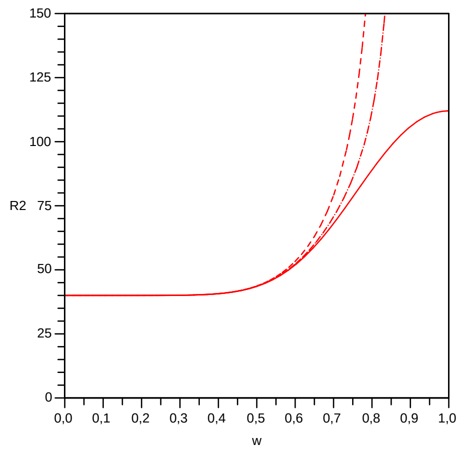
- Holographic renormalization:
  $\Rightarrow$ Existence of a Dynamical Scaling

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

The Moving Black Hole in 5-d

- Holographic Renormalization:
  $\Rightarrow$ Regularity Criterium

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



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

Nonsingular Dual Geometry $\Leftrightarrow$ Perfect Fluid

- Asymptotic metric
  $\Rightarrow$ Black Hole (Brane) Moving off in the 5th dimension

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

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

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

Some recent Results

- Going beyond perfect fluid

  In-flow Viscosity, Relaxation time, Transport Coeff., etc...

  Janik, Heller, Bak, Benincasa, Buchel, Nakamura, Sin,......
  Kinoshita, Mukoyama, Nakamura, Oda,Natsuume, Okamura,...

$$\boxed{\partial_\tau \epsilon = -\frac{4}{3}\frac{\epsilon}{\tau} + \frac{\eta}{\tau^2} + \cdots \Rightarrow \frac{\eta}{s} = \frac{1}{4\pi}}$$

- Going beyond boost-invariance

  General hydrodynamic equations from AdS/CFT

  Bhattacharyya, Hubeny, Minwalla, Ranganami, Loganayagam,...

$$T^{\mu\nu}_{rescaled} = \underbrace{(\pi T)^4(\eta^{\mu\nu} + 4u^\mu u^\nu)}_{perfect\ fluid} - \underbrace{2(\pi T)^{3\mu\nu}}_{viscosity} +$$

$$+ \underbrace{(\pi T^2)\left(\log 2T^{\mu\nu}_{2a} + 2T^{\mu\nu}_{2b} + (2-\log 2)\left(\frac{1}{3}T^{\mu\nu}_{2c} + T^{\mu\nu}_{2d} + T^{\mu\nu}_{2e}\right)\right)}_{second\ order\ hydrodynamics}$$

- *Going beyond hydrodynamics?*

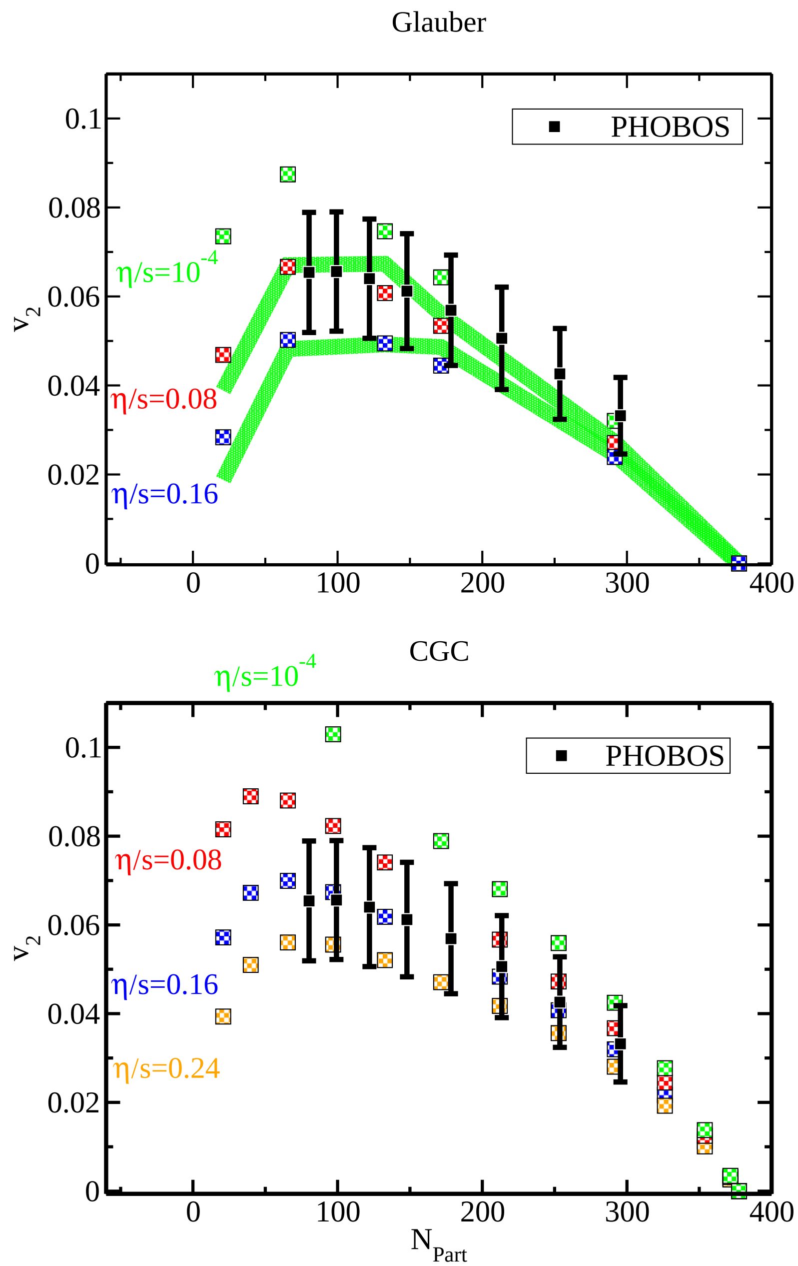
  Physics in the expanding plasma: Fundamental flavours, mesons,... *Janik, Heller, Große, Surowka ...*

  Modeling heavy-ion collisions: see next...

Strings *vs.* Reality: Elliptic Flow

Ollitrault (1992)

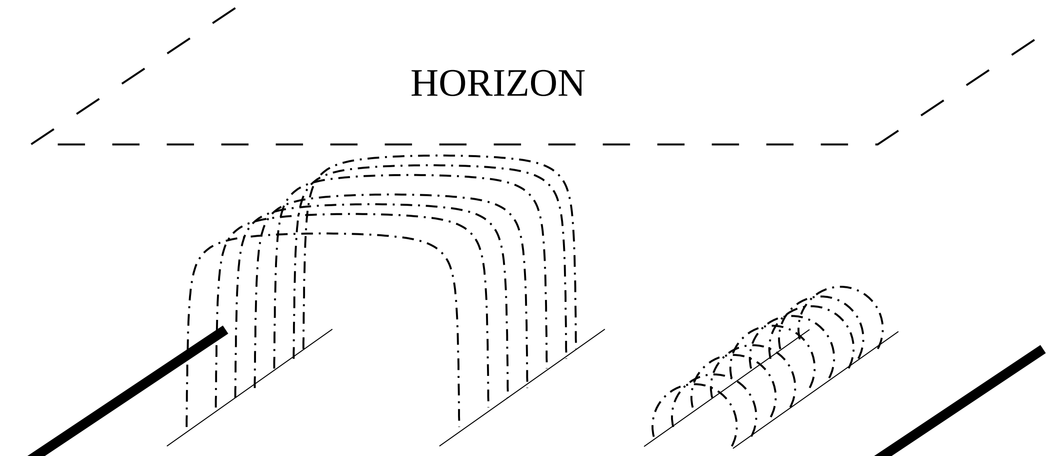
$$\frac{\partial N}{\partial \Phi} \propto 1 + 2\, v_2 \cos 2\Phi$$



Luzum, Romatschke (2008)

Gravity dual of high-energy collisions

- Conditions:
  Defining Probes and confining *vs.* conformal geometry
- One Holograhic method
  Wilson Lines $\Rightarrow$ Minimal Surfaces



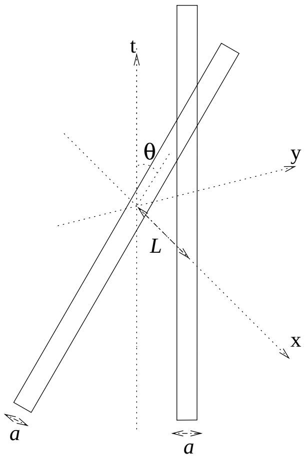
$$\langle e^{iP\int_C \vec{A}\cdot\vec{dl}}\rangle = \int_{\Sigma} e^{-\frac{Area(\Sigma)}{\alpha'}} \approx e^{-\frac{Min.Area}{\alpha'}} \times Fluctuations$$

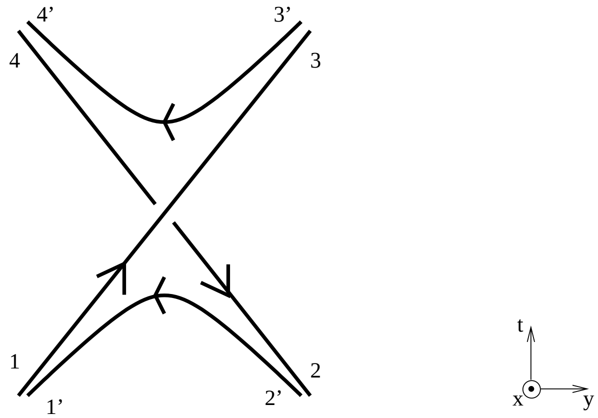
- Exemple: The Perimeter *vs.* Area law
  Conformal case : $\langle Wilson\ Lines\rangle = e^{T*V(L)} \sim e^{T\times 1/L}$
  Confining case :$\langle Wilson\ Lines\rangle = \quad e^{T*V(L)} \sim e^{T\times L}$

AMPLITUDES at STRONG COUPLING

- SOFT AMPLITUDES

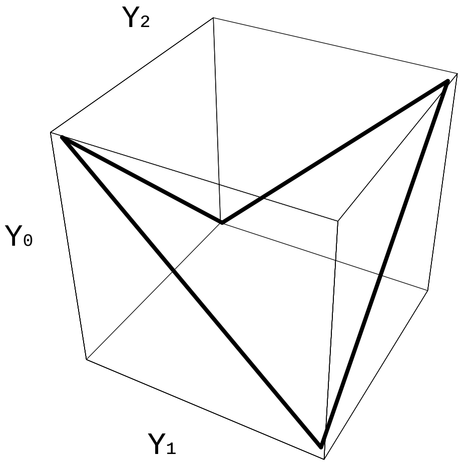
Regge trajectories: R.Janik, RP (2000)

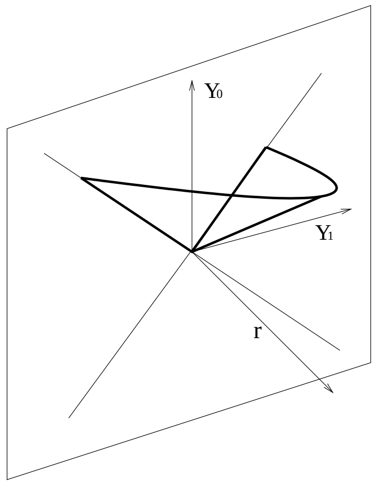




- HARD AMPLITUDES

S^4YM amplitudes: Alday, Maldacena (2007)



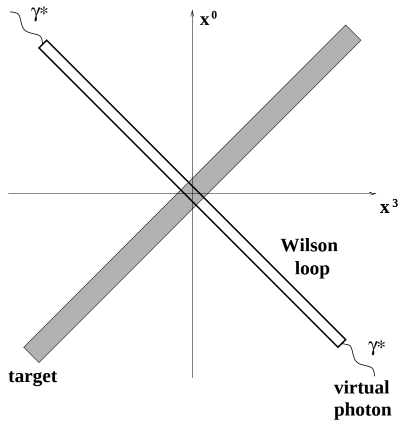


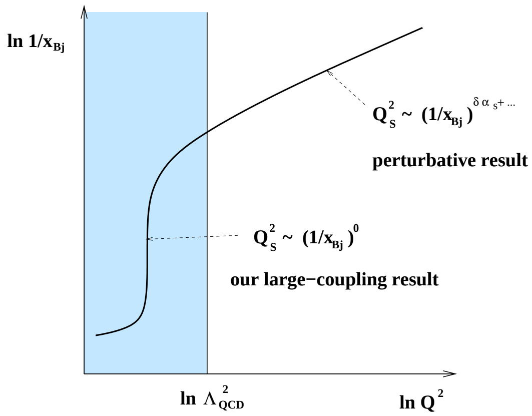
DEEP-INELASTIC AMPLITUDES

Polchinski, Strassler (2003); Hata, Iancu, Mueller (2007)
Ballon Bayona, Boschi-Filho,Braga (2007); Albacete,Kovchegov,Taliotis (2008)
...

- DIS at small Q^2

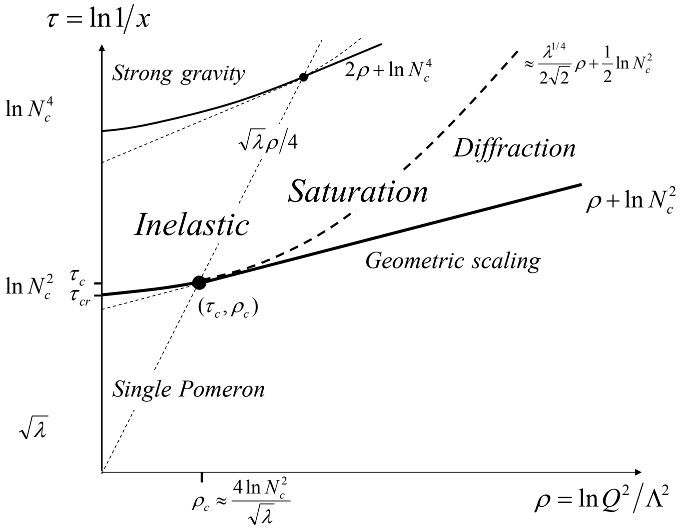
Albacete,Kovchegov,Taliotis (2008)





- DIS at Strong Coupling

Hata, Iancu, Mueller (2007)



Prospects

In progress:

- Gauge-Gravity Correspondence
  A promising way towards QCD at strong coupling
- Results on AdS/CFT $\rightarrow$ S^4QCD Hydrodynamics
  Einstein *vs.* Navier-Stokes, Thermalization,...
- Other studies
  Jet Quenching, Quark Dragging, and many others...

What in front of us?

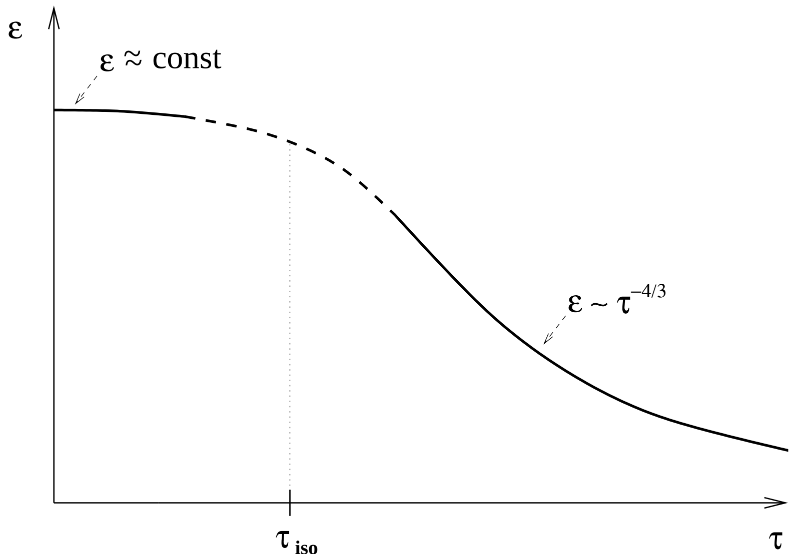
- More Theoretical Work
  Gauge/Gravity beyond AdS/CFT
- More "Translation" Work
  Formulating Observables: V_2, Diffraction, Soft/Hard Interplay
- From S^4QCD to S^0QCD ?
  Construct the "Gravity Dual" of QCD

Why all that seems to work?

EXTRA SLIDES

AdS/CFT: Anisotropy at small τ

Kovchegov, Taliotis arXiv:0705.1234



Evaluation of The Isotropization/Thermalization time

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

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

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

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