EXPANDING PLASMA AT STRONG COUPLING

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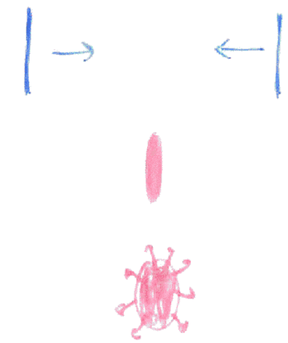
1. MOTIVATION
2. AdS/CFT FRAMEWORK
   - EXAMPLES
3. EXPANDING BOOST-INVARIANT PLASMA
4. 'THERMALIZATION' IN THE EXPANDING PLASMA SYSTEM
5. FLAVOURS — " — " — " —
6. PARTICLE PRODUCTION
7. ANISOTROPIC PLASMA AT STRONG COUPLING
8. SUMMARY / OUTLOOK

WORK WITH R. PESHANSKI
M. HELLER
J. GROSSE, P. SUROWKA
A. BUCHEL, P. BENINCASA
P. WITASZCZYK

6+7: WORK IN PROGRESS

AIM: USE AdS/CFT TO STUDY DYNAMICAL TIME-DEPENDENT PROCESSES FOR $\mathcal{N}=4$ PLASMA



DIFFICULT — COLLISION

V. DIFFICULT — INITIAL 'THERMALISATION' ISOTROPISATION?

DOABLE — EXPANSION OF THE FIREBALL

- STUDY PROPERTIES OF THE EXPANDING PLASMA SYSTEM
  - EQUILIBRATION TIME
  - INFLUENCE ON FUNDAMENTAL FLAVOURS
  - PARTICLE PRODUCTION ?
- STUDY PLASMA IN AN OUT OF EQUILIBRIUM SETTING
  - ANISOTROPIC $\mathcal{N}=4$ PLASMA AT STRONG COUPLING

$\mathcal{N}=4$ PLASMA VS. QCD PLASMA

SIMILARITIES :

- DECONFINED PHASE
- STRONGLY COUPLED

DIFFERENCES :

- NO RUNNING COUPLING
- CONFORMAL EQUATION OF STATE
- NO CONFINEMENT/DECONFINEMENT PHASE TRANSITION

→ PLASMA FIREBALL COOLS INDEFINITELY

→ AT VERY HIGH ENERGY DENSITIES COUPLING REMAINS STRONG

....

BUT :

- TOY MODEL WHERE WE MAY COMPUTE FROM 'FIRST PRINCIPLES'
- DISCOVER SOME UNIVERSAL PROPERTIES ?
- FOR $\mathcal{N}=4$ PLASMA AdS/CFT SETTING IS TECHNICALLY SIMPLEST
- EVENTUALLY ONE MAY CONSIDER MORE REALISTIC THEORIES WITH AdS/CFT DUALS...

COMPARISON WITH PREVIOUS CALCULATIONS OF VISCOSITY ETC.

→ FLUCTUATIONS AROUND STATIC PLASMA AT FIXED T — LINEARIZED HYDRODYNAMICS

||

FLUCTUATIONS AROUND BLACK HOLE GEOMETRY

- HYDRODYNAMIC MODES
- TRANSPORT COEFFICIENTS
- AND MORE...

HERE:

- STUDY HYDRODYNAMICS IN THE NONLINEAR REGIME
  - NONTRIVIAL CONSISTENCY CHECK
- STUDY CONFIGURATIONS FAR AWAY FROM BEING A THERMAL SYSTEM (OR FAR FROM HYDRODYNAMICS)

$\mathcal{N}=4$ SYM on $\mathbb{R}^4$ $\equiv$ SUPERSTRINGS ON $AdS^5 \times S^5$

↑

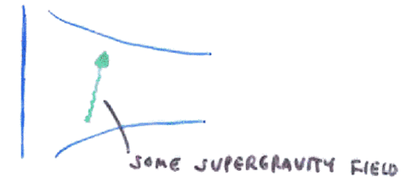
LOOK FOR CONFIGURATIONS CORRESPONDING TO A PLASMA SYSTEM

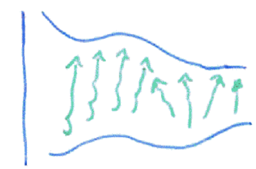
EMPTY SPACE

(VACUUM)

AdS_5 $(\times S^5)$

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

GAUGE THEORY SIDE		STRING THEORY SIDE
STATE WITH GIVEN EXPECTATION VALUES OF THE CORRESPONDING OPERATOR		
$\langle T_{\mu\nu} \rangle \neq 0$	$\longleftrightarrow$	GRAVITON $g_{\mu\nu}$
$\langle \mathrm{tr}\, F^2 \rangle \neq 0$	$\longleftrightarrow$	DILATON ϕ
GENERIC OPERATOR	$\longleftrightarrow$	GENERIC STRING STATE



DESCRIBED BY SOME BACKGROUND GEOMETRY :

$$\langle T_{\mu\nu} \rangle = \ldots \quad \longleftrightarrow \quad ds^2 = \frac{g_{\mu\nu}(x^\mu, z)\, dx^\mu dx^\nu + dz^2}{z^2}$$

MACROSCOPIC SPACETIME PROFILE OF ENERGY MOMENTUM TENSOR

HOLOGRAPHIC RENORMALIZATION

DE HARO, SOLODUKHIN, SKENDERIS

① HOW TO READ OFF $\langle T_{\mu\nu} \rangle$ FROM A GIVEN (5D) GEOMETRY ?

- ADOPT FEFFERMAN-GRAHAM COORDINATES

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

- LOOK AT THE EXPANSION NEAR THE BOUNDARY $z=0$

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

$g^{(2)}_{\mu\nu} = 0$

PHYSICAL 4D METRIC FOR THE GAUGE THEORY ($g^{(0)}_{\mu\nu} = \eta_{\mu\nu}$ HERE)

$$\boxed{\langle T_{\mu\nu} \rangle = \frac{N_c^2}{2\pi^2} \cdot g^{(4)}_{\mu\nu}}$$

② GIVEN SOME $\langle T_{\mu\nu} \rangle$ HOW TO RECONSTRUCT THE DUAL (5D) GEOMETRY ?

- FIND SOLUTION OF EINSTEIN EQUATIONS

$$(*) \qquad R_{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} R + \underset{\substack{\parallel \\ -6}}{\Lambda}\, g_{\alpha\beta} = 0$$

WITH THE BOUNDARY CONDITIONS

$$g_{\mu\nu} = \eta_{\mu\nu} + z^4 \underset{\substack{\& \\ \langle T_{\mu\nu} \rangle}}{g^{(4)}_{\mu\nu}} + \ldots$$

- (*) IMPLY $\quad g^{(4)\ \mu}_{\ \ \mu} = 0$

$$D_\mu g^{(4)\mu\nu} = 0$$

- FOR **ANY** SUCH $g^{(4)}_{\mu\nu}$ ONE CAN COMPUTE RECURSIVELY HIGHER ORDER TERMS IN $g_{\mu\nu}$!!

OUR FRAMEWORK:

RJ, R. PESCHANSKI

- FOR GENERIC PLASMA CONFIGURATIONS CONSTRUCT DUAL

$$\langle T_{\mu\nu}(x^\mu)\rangle \longrightarrow g_{\mu\nu}(x^\mu, z)$$

- PHYSICAL CONFIGURATION SHOULD CORRESPOND TO NONSINGULAR GEOMETRY

- STUDY PROPERTIES OF THE BACKGROUND....

EXAMPLE 1

CONSTANT $\langle T_{\mu\nu}\rangle = \begin{pmatrix} 3 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix} \cdot \underset{\displaystyle \frac{1}{z_0^4}}{\underset{\displaystyle \parallel\!\!\!|}{\mathrm{const}}} \cdot \frac{N_c^2}{2\pi}$

EINSTEIN EQUATIONS

$$= \begin{pmatrix} \varepsilon & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix} \quad \text{WITH } \varepsilon = 3p$$

$$ds^2 = -\frac{\left(1 - z^4/z_0^4\right)^2}{1 + z^4/z_0^4}\frac{dt^2}{z^2} + \left(1 + \frac{z^4}{z_0^4}\right)\frac{d\vec{x}^2}{z^2} + \frac{dz^2}{z^2}$$

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

STANDARD PLANAR AdS BLACK HOLE

$$ds^2 = -\left(1 - \frac{\tilde{z}^4}{\tilde{z}_0^4}\right)\frac{dt^2}{\tilde{z}^2} + \frac{d\vec{x}^2}{\tilde{z}^2} + \frac{1}{1 - \frac{\tilde{z}^4}{\tilde{z}_0^4}}\frac{d\tilde{z}^2}{\tilde{z}^2}$$

$\tilde{z}_0 = \frac{z_0}{\sqrt{2}}$ ← LOCATION OF THE HORIZON

EXAMPLE 2 PLANAR SHOCKWAVE

- INTRODUCE LIGHT-CONE COORDINATES

$$x^- = t - y \qquad x^+ = t + y$$

- PUT $T_{--} = \mu\,\delta(x^-)$

EINSTEIN EQUATIONS

$$ds^2 = \frac{-dx^- dx^+ + \mu z^4 \delta(x^-)\, dx^{-2} + dx_\perp^2}{z^2} + \frac{dz^2}{z^2}$$

- MODELS AN INFINITELY BOOSTED NUCLEUS
- STUDY COLLISIONS OF TWO SUCH SHOCKWAVES....

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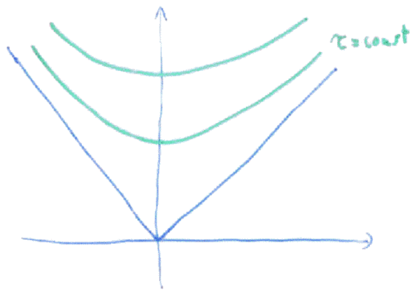
- BOOST INVARIANT PLASMA EXPANSION /BJORKEN '83



ASSUME:

- NO DEPENDENCE ON RAPIDITY y
- NO DEPENDENCE ON TRANSVERSE COORDINATES $\vec{x}_\perp$

THEN

$$\left.\begin{array}{l} \partial_\mu T^{\mu\nu} = 0 \\ T^\mu_\mu = 0 \end{array}\right\} \Rightarrow \begin{array}{l} T_{\tau\tau} = \varepsilon(\tau) \\ T_{yy} = -\tau^2\left(\tau \frac{d\varepsilon}{d\tau} + \varepsilon\right) \\ T_{xx} = \frac{1}{2}\tau\frac{d\varepsilon}{d\tau} + \varepsilon \end{array}$$

- $\varepsilon(\tau)$ – ENERGY DENSITY IN THE LOCAL REST FRAME

Q: DETERMINE $\varepsilon(\tau)$

- WEAK COUPLING → FREE STREAMING

$$\varepsilon(\tau) = \frac{1}{\tau}$$

- PERFECT FLUID ASSUMPTION

$$\varepsilon(\tau) = \frac{1}{\tau^{4/3}}$$

- FLUID WITH VISCOSITY $\eta = \frac{\eta_0}{\tau}$ $\quad \| \quad \eta \propto T^3$

$$\varepsilon(\tau) = \frac{1}{\tau^{4/3}}\left(1 - \frac{2\eta_0}{\tau^{2/3}} + \dots \right)$$

- SECOND ORDER VISCOUS HYDRODYNAMICS $\eta, \tau_\pi, \dots$

$$\varepsilon(\tau) = \frac{1}{\tau^{4/3}}\left(1 - \frac{2\eta_0}{\tau^{2/3}} + \frac{\#}{\tau^{4/3}} + \dots \right)$$

\# DEPENDS ON VERSION OF THE FORMALISM

HOW CAN THIS BEHAVIOR BE SEEN IN AdS/CFT ?

- FOCUS ON LATE TIME ASYMPTOTICS

$$\varepsilon(\tau) = \frac{1}{\tau^s}$$

- CONSTRUCT DUAL GEOMETRY WITH SAME SYMMETRIES

$$ds^2 = \frac{1}{z^2}\left(-e^{a(z,\tau)}d\tau^2 + e^{b(z,\tau)}\tau^2 dy + e^{c(z,\tau)}dx_\perp^2\right) + \frac{dz^2}{z^2}$$

- LOOK AT

$$\underbrace{a(z,\tau) = -\frac{z^4}{\tau^s} + z^6 a_6(\tau) + z^8 a_8(\tau) + \dots}_{\text{PICK LARGE } \tau \text{ BEHAVIOUR}}$$

$$\Downarrow$$

$$a(z,\tau) = a(v) + \dots, \qquad v \equiv \frac{z}{\tau^{s/4}}$$

$$\Downarrow$$

SOLVE EINSTEIN'S EQUATIONS (ODE's !)

• SOLUTION:

$$a(v) = A(v) - 2\,m(v)$$

$$b(v) = A(v) + (2s-2)\,m(v)$$

$$c(v) = A(v) + (2-s)\,m(v)$$

WHERE

$$A(v) = \frac{1}{2}\left(\log\left(1+\Delta(s)v^4\right) + \log\left(1-\Delta(s)v^4\right)\right)$$

$$m(v) = \frac{1}{4\Delta(s)}\left(\log\left(1+\Delta(s)v^4\right) - \log\left(1-\Delta(s)v^4\right)\right)$$

AND

$$\Delta(s) = \sqrt{\frac{3s^2-8s+8}{24}}$$

↝ AGREES WITH SCALING LIMIT OF THE POWER SERIES SOLUTIONS

↝ VALID ONLY FOR $\tau \to \infty$ BUT ANALYTIC

↝ ONE CAN STUDY CURVATURE SINGULARITIES

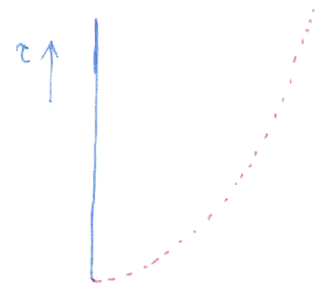
COMPUTE

$$R_{\mu\nu\alpha\beta}R^{\mu\nu\alpha\beta} = R_0(v) + \frac{1}{\tau^{4/3}}R_2(v) + \ldots$$

NONSINGULAR ONLY FOR $s = \frac{4}{3}$

• LATE TIME DYNAMICS IS DESCRIBED BY PERFECT FLUID HYDRODYNAMICS

• GEOMETRY LOOKS LIKE A MOVING BLACK HOLE



$$z_0 \sim \tau^{1/3} \quad \Rightarrow \quad T \sim \frac{1}{\tau^{1/3}}$$

ENTROPY PER UNIT RAPIDITY ~ const

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

ADVOCATED QUALITATIVELY: SHURYAK, SANG-JIN SIN, ZAHED

IS $\varepsilon(\tau) = \frac{1}{\tau^{4/3}}$ EXACT ?

$$R_{\mu\nu\alpha\beta}R^{\mu\nu\alpha\beta} = \underbrace{R_0(v)}_{\text{NONSINGULAR}} + \frac{1}{\tau^{4/3}} R_2(v) + \ldots$$

$R_2(v)$: 4TH ORDER POLE SINGULARITY

• SET $\varepsilon(\tau) = \frac{1}{\tau^{4/3}}\left(1 + \frac{\#}{\tau^r} + \ldots\right)$

$$R_{\mu\nu\alpha\beta}R^{\mu\nu\alpha\beta} = \underbrace{R_0(v)}_{\text{NONSINGULAR}} + \frac{1}{\tau^r}\underbrace{R_1(v)}_{\text{NONSINGULAR}} + \frac{1}{\tau^{2r}}\underbrace{\tilde{R}_1(v)}_{\text{SINGULAR}} + \frac{1}{\tau^{4/3}}\underbrace{R_2(v)}_{\text{SINGULAR}} + \ldots$$

MAY CANCEL WITH EACH OTHER

IF $r = \frac{2}{3}$ AND $\#$ IS FIXED

THEN

$$\varepsilon(\tau) = \frac{1}{\tau^{4/3}}\left(1 - \frac{2\eta_0}{\tau^{2/3}} + \ldots\right)$$

NAKAMURA, SIN

GEOMETRY $\frac{1}{\tau^{4/3}}$

EXACTLY THE SUBLEADING CORRECTION ASSOCIATED WITH VISCOSITY

η_0 FIXED TO $\eta_0 = 2^{-\frac{1}{2}}3^{-\frac{3}{4}}$ RJ

COMPATIBLE WITH $\frac{\eta}{s} = \frac{1}{4\pi}$

HELLER, RJ

• GO TO HIGHER ORDER

$$\varepsilon(\tau) = \frac{1}{\tau^{4/3}}\left(1 - \frac{2\eta_0}{\tau^{2/3}} + \frac{\#}{\tau^{4/3}} + \ldots\right)$$

• CURVATURE

$$R_{\mu\nu\alpha\beta}R^{\mu\nu\alpha\beta} = R_0(v) + \frac{1}{\tau^{2/3}}R_1(v) + \frac{1}{\tau^{4/3}}R_2(v) + \frac{1}{\tau^2}R_3(v) + \ldots$$

4TH ORDER POLE + LOGARITHMIC + FINITE

4TH ORDER POLE $\Downarrow$ FIXES '#' $\Downarrow$ RELAXATION TIME IN 2^{nd} ORDER HYDRODYNAMICS

UNIVERSALITY ?

(SAME RESULT FOR KLEBANOV-WITTEN THEORY)

LOGARITHMIC $\rightarrow$ REMAINS !

A. BUCHEL TALK DURING THE CONFERENCE

SIGN OF INSTABILITIES

SEEN AT WEAK COUPLING ????

(VIOLATIONS OF BOOST INVARIANCE)

?

BUCHEL, BONANCASA, HELLER, RJ

'THERMALIZATION' IN THE EXPANDING PLASMA SYSTEM

Q: SUPPOSE WE PERTURB THE EXPANDING PLASMA

HOW WILL THE PERTURBATION BEHAVE WITH TIME ?

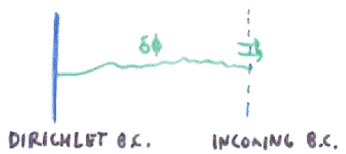
- CONSIDER STATIC PLASMA

HOROWITZ, HUBENY '99
STARINETS '02

$$\delta T_{xy} \longrightarrow \delta g_{xy}$$

$$\delta(B^2 - E^2) \longrightarrow \delta\phi$$

- QUASINORMAL MODES OF THE STATIC BLACK HOLE



- FLUCTUATIONS DECAY EXPONENTIALLY WITH TIME

LOWEST FREQUENCY (IN THE SCALAR CHANNEL) :

$$e^{-i\,\omega_{static}(T)t}$$

WHERE

$$\omega_{static}(T) = (3.1194 - 2.7467i)\cdot \pi T$$

DOES THE EXPANDING PLASMA BEHAVE SIMILARLY ?

RJ, R. PESCHANSKI

- SCALAR CHANNEL PERTURBATION OF THE PERFECT FLUID GEOMETRY

SEPARATION OF VARIABLES FOR LARGE τ

$$\sqrt{\tau}\, J_{\pm\frac{3}{4}}\left(\frac{3}{2}\omega\tau^{\frac{2}{3}}\right) \cdot \phi_\omega\left(v = \frac{z}{\tau^{1/3}}\right)$$

SATISFIES SAME EQUATION AS FOR STATIC BUT WITH SCALING VARIABLE v

$\longrightarrow$ SAME ω

$$\tau^{\frac{1}{6}}\, e^{\frac{3}{2} i\omega\tau^{\frac{2}{3}}}$$

GIVEN BY STATIC QNM

- DAMPING : $e^{-\frac{3}{2}\, 2.7467\,\cdot\,\tau^{\frac{2}{3}}}$

// UNITS : $z_0 = \tau^{1/3}$ IN F-G COORDINATES

- EXPANDING PLASMA IS STABLE UNDER PERTURBATIONS
- ATTRACTOR GEOMETRY ?
- PERFECT FLUID GEOMETRY $\rightsquigarrow$ 'ADIABATIC' APPROXIMATION

$$\omega(T)t \rightsquigarrow \int \omega(T(\tau))\,d\tau$$

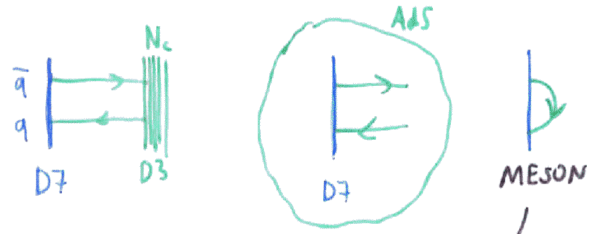
BUT NOTE POWER-LAW PREFACTORS + VISCOSITY CORRECTIONS...

FUNDAMENTAL FLAVOURS IN THE EXPANDING PLASMA

- CONSIDER $\mathcal{N}=4$ SYM + ONE ADDITIONAL FLAVOUR ($\mathcal{N}=2$)

CAUTION : THIS THEORY DOES NOT HAVE CHIRAL SYMMETRY BREAKING..

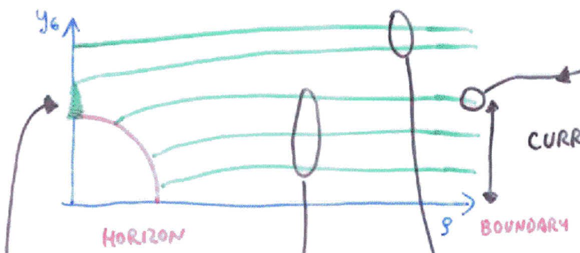
- AdS/CFT DESCRIPTION
  - EMBED A D7 BRANE IN THE GEOMETRY



LIGHTEST MESONS : FLUCTUATIONS OF THE D7 BRANE EMBEDDING (OR D7 GAUGE FIELDS)

FINITE TEMPERATURE CASE (STATIC PLASMA)

- EMBED A D7 BRANE INTO THE BLACK HOLE GEOMETRY $y_6(\rho)$



READ OFF $\langle\bar{\Psi}\Psi\rangle$ + SUSY..

CURRENT QUARK MASS

'CONSTITUENT' MASS

'MINKOWSKI EMBEDDINGS'

MESONS ARE STABLE

LARGE m

'BLACK HOLE EMBEDDINGS'

MESONS DISSOCIATE

SMALL m

- FIX m, T
- GET EMBEDDING
- READ OFF $\langle\bar{\Psi}\Psi\rangle$
- STUDY FLUCTUATIONS
- OBTAIN MESON MASSES

J. GROSSE, RJ, P. SUROWKA

QUESTION: HOW DOES THE EXPANDING PLASMA MODIFY FLAVOR PHYSICS ?

- USE LATE TIME EXPANSION → 'MINKOWSKI EMBEDDING'
- EMBED D7 BRANE INTO PLASMA GEOMETRY (INCLUDING VISCOSITY)

$$y_6(\rho,\tau) = m + \left(-\frac{\#}{\tau^{4/3}}\left(1-\frac{\#}{\tau^{2/3}}+\dots\right)\right)\cdot\frac{\rho^4+3\rho^2m^2+3m^4}{(m^2+\rho^2)^3} + \dots$$

- READ OFF THE CONDENSATE

$$\langle\bar\psi\psi\rangle \propto \#\frac{\varepsilon^2(\tau)}{m_q^5}$$

- LOOK AT FLUCTUATIONS → MESONS

MAJOR COMPLICATION: LACK OF SEPARABILITY (PDE)

- ANSATZ FOR FLUCTUATIONS

$$\delta\phi = \sqrt{\frac{\int\omega(\tau)d\tau}{\omega(\tau)\cdot\tau}}\; \begin{matrix}J_0\\ Y_0\end{matrix}\left(\int\omega(\tau)d\tau\right)\cdot\left(f_0(\rho)+\frac{1}{\tau^{4/3}}f_1(\rho)+\frac{1}{\tau^2}f_2(\rho)+\dots\right)$$

→ DETERMINE τ-DEPENDENT FREQUENCY $\omega(\tau)$

LOWEST MODE

$$\omega(\tau) = \frac{4\pi}{\sqrt{\lambda}}\left(m_q - \frac{3\lambda^2\varepsilon_0}{80\pi^4 m_q^3}\frac{1}{\tau^{4/3}}\left(1-\frac{2\eta_0}{\varepsilon_0^{1/4}}\frac{1}{\tau^{2/3}}+\dots\right)\right)$$

// CAUTION: NOT REALISTIC MODEL OF QCD – NO χSB !

- HOW DO THESE MODES LOOK LIKE ON THE BOUNDARY ?

$$\delta\phi_{4D}(x^\mu) = \lim_{\rho\to\infty}\rho^2\,\delta\phi(x^\mu,\rho)$$

• THESE 4D MODES $\delta\Phi_{4D}(x^\mu)$ SATISFY

$$\boxed{\Box\,\delta\Phi_{4D} + \omega^2(\tau)\,\delta\Phi_{4D} = 0}$$

↑ TYPICAL FORM AS FOR SCALAR FIELDS IN A COSMOLOGICAL SETTING !

⟶ EXPECT PARTICLE PRODUCTION

WORK IN PROGRESS

J. GROSSE, RJ, P. SURÓWKA

ANISOTROPIC PLASMA AT STRONG COUPLING

MOTIVATION: PLASMA INSTABILITIES AT WEAK COUPLING

• ANISOTROPIC GLUON MOMENTUM DISTRIBUTION

→ SMALL FLUCTUATIONS (UNSTABLE MODES) ⟵

→ TIME EVOLUTION FROM INITIAL CONDITIONS

SETUP STUDY ANISOTROPIC PLASMA AT STRONG COUPLING

$$T_{\mu\nu} = \begin{pmatrix} \varepsilon & & & \\ & p_{\parallel} & & \\ & & p_{\perp} & \\ & & & p_{\perp} \end{pmatrix}$$

$p_{\parallel} + 2p_{\perp} = \varepsilon$

// MINKOWSKI COORDINATES !

CONSIDER STATIC CONFIGURATION

WORK IN PROGRESS: RJ, P. WITASZCZYK

FRAMEWORK

$$T_{\mu\nu} \longrightarrow ds^2 = \frac{1}{z^2}\left(-a(z)\,dt^2 + b(z)\,dx_{\parallel}^2 + c(z)\,d\vec{x}_{\perp}^{\,2}\right) + \frac{dz^2}{z^2}$$

• EXACT SOLUTION

$$a(z) = (1+Az^4)^{\frac{1}{2}-\frac{1}{4}\sqrt{36-2B^2}}\;(1-Az^4)^{\frac{1}{2}+\frac{1}{4}\sqrt{36-2B^2}}$$

$$b(z) = (1+Az^4)^{\frac{1}{2}-\frac{B}{3}+\frac{1}{12}\sqrt{36-2B^2}}\;(1-Az^4)^{\frac{1}{2}+\frac{B}{3}-\frac{1}{12}\sqrt{36-2B^2}}$$

$$c(z) = (1+Az^4)^{\frac{1}{2}+\frac{B}{6}+\frac{1}{12}\sqrt{36-2B^2}}\;(1-Az^4)^{\frac{1}{2}-\frac{B}{6}-\frac{1}{12}\sqrt{36-2B^2}}$$

• A AND B RELATED TO ε, $p_{\parallel}$, $p_{\perp}$

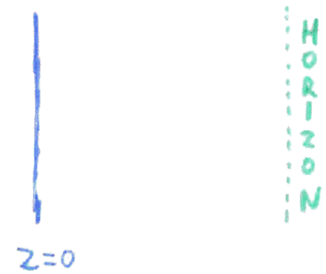
$$\varepsilon = \frac{1}{2}\sqrt{36-2B^2}\,A$$

$$p_{\parallel} = \left(\frac{1}{6}\sqrt{36-2B^2} - \frac{2}{3}B\right)A$$

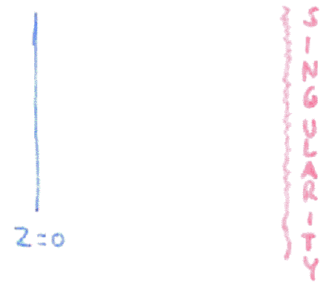
$$p_{\perp} = \left(\frac{1}{6}\sqrt{36-2B^2} + \frac{1}{3}B\right)A$$

$\longrightarrow$ B MEASURES THE ANISOTROPY

• $B=0$ REDUCES TO STATIC BLACK HOLE



• $B \neq 0$



• LOOK AT SMALL FLUCTUATIONS...

INSTABILITIES ???

WORK IN PROGRESS

SUMMARY & OUTLOOK

- VERY GENERAL FRAMEWORK FOR STUDYING TIME-DEPENDENT DYNAMICAL PROCESSES OR OUT-OF-EQUILIBRIUM CONFIGURATIONS
- AdS/CFT $\longrightarrow$ HYDRODYNAMICAL EXPANSION WITH SPECIFIC TRANSPORT COEFFICIENTS
- LEFTOVER LOGARITHMIC SINGULARITIES (?)
- EXPANDING PLASMA SYSTEM IS STABLE AGAINST PERTURBATIONS
- TIME DEPENDENT MESONIC FREQUENCIES
- PARTICLE PRODUCTION ?
- ANISOTROPIC PLASMA AT STRONG COUPLING INSTABILITIES ??

MANY OPEN QUESTIONS

- DEFINITIONS OF ENTROPY/TEMPERATURE
- GLOBAL STRUCTURE ?
- MEANING OF LOGARITHMIC SINGULARITIES
- INITIAL THERMALIZATION
- SCALE, PHASE TRANSITION ?