Perugia, June 24th 2010.

D3-D7 Quark-Gluon Plasmas

Francesco Bigazzi

K.U. Leuven

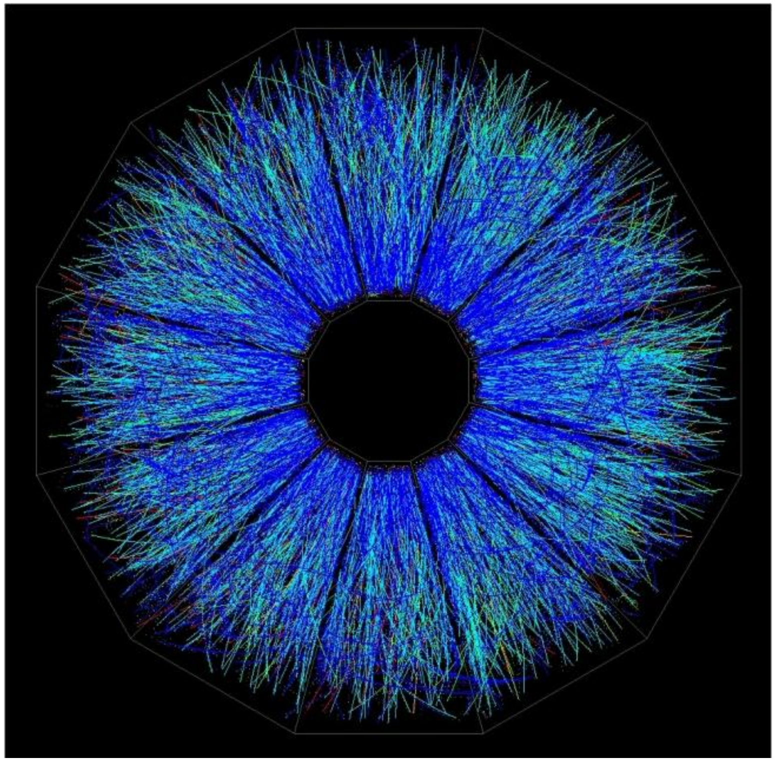
based on works with

Aldo L. Cotrone (*KU, Leuven*), Angel Paredes (*U. Barcelona*),
Alfonso V. Ramallo, Javier Mas, Javier Tarrío (*U. Santiago de Compostela*)

Plan

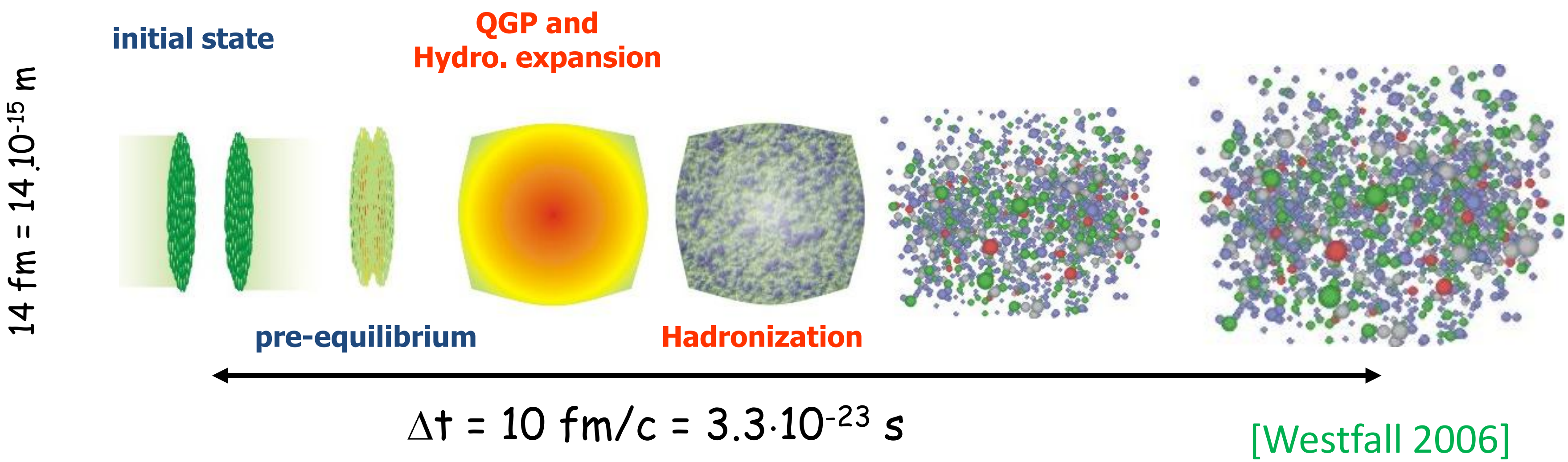
- Motivations: quark-gluon plasma @ RHIC
- D3-D7 plasmas
- Thermodynamics and hydrodynamics
- Novel universal results

Motivations:
Heavy ion collisions at RHIC



[3000 particles created in a central Au+Au collisions at RHIC (STAR)]

Motivations

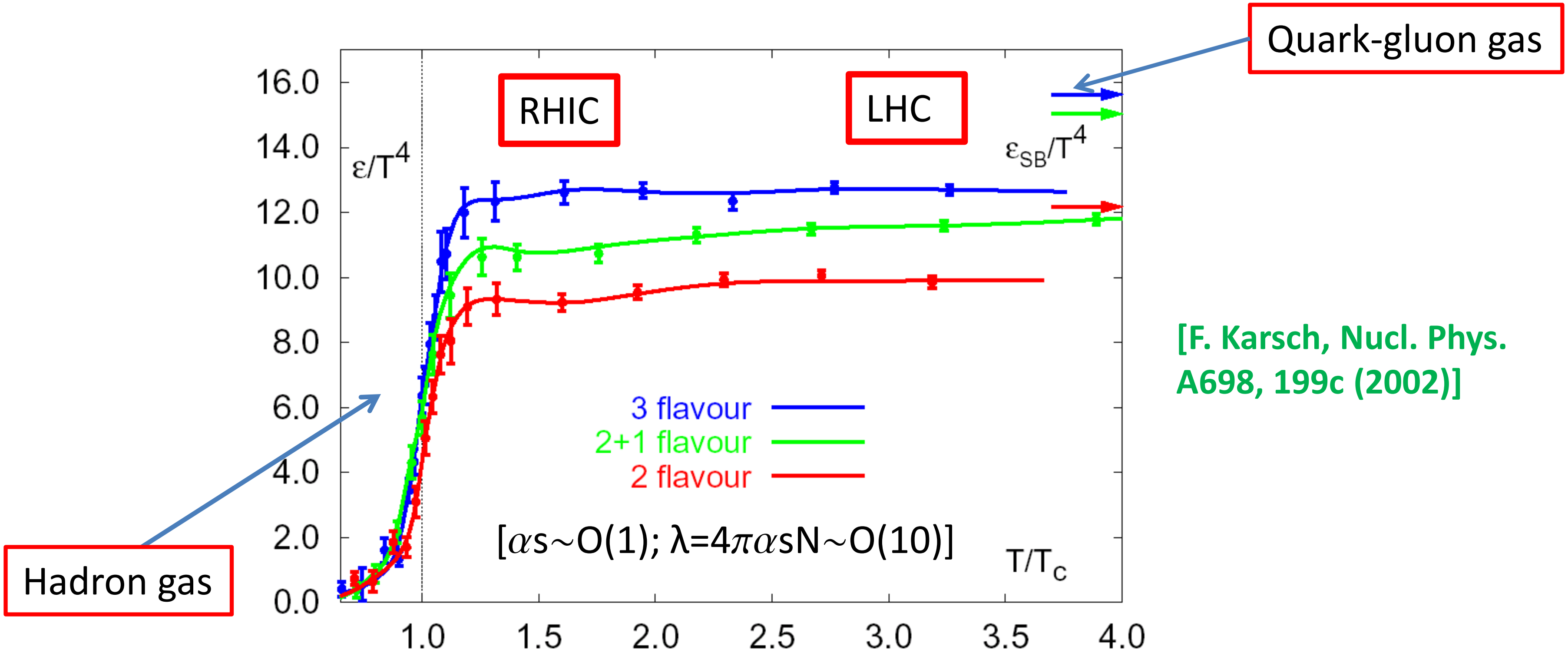


[Westfall 2006]

- Au-Au collision at Relativistic Heavy Ion Collider (RHIC)
- At T>Tc a plasma of quarks and gluons.
- Elliptic flow, jet quenching... : QGP probably strongly coupled
- Liquid with very low viscosity. Model by relativistic hydrodynamics
- A challenge for theoretical physics: pQCD not very useful

Motivations

- Thermodynamics (equilibrium) properties from Lattice QCD



[F. Karsch, Nucl. Phys. A698, 199c (2002)]

- At T>Tc, small T dependence (nearly conformal)
- At T>Tc , 80% of free Stefan-Boltzmann gas of quarks and gluon
- What about hydrodynamics? On lattice problems with real-time

Motivations

- QGP@RHIC nearly conformal, strongly coupled
- $\eta/s \leq 4(1/4\pi)$ (hydro simulations, elliptic flow)
- $\varepsilon/\varepsilon_0 \sim 80\%$ (lattice QCD)

- Thermal CFTs (e.g. *N=4 SYM)* with AdS5-BH dual as benchmarks!
- $\eta/s = 1/4\pi$ [Policastro, Son, Starinets 2001]
- $\varepsilon/\varepsilon_0 = s/s_0 = 3/4$ [Witten 1998]
- Using gauge/gravity duality, we can study real-time processes
- Focus on universal properties (e.g. $\eta/s=(1/4\pi)$ for every plasma with gravity dual [Kovtun, Son, Starinets 2004])

Motivations

- Prototypes: planar strongly coupled thermal quivers on Nc D3-branes at CY3 cones.

  $\mathcal{N}$=1 superconformal theories at T=0
- Dual description (T≠0) : IIB on AdS5 (black hole) x X5, constant dilaton and F5 RR flux. X5: Sasaki-Einstein base of the cone.

- $\lambda = g^2$ Nc >> 1, Nc>>1
- Matter fields in 2-index representation (adjoint, bifundamental...): no quarks (i.e fundamental matter fields)!
- Goal: add dynamical flavors and study their effects on the properties of the strongly coupled plasmas

D3-D7 plasmas

D3-D7 plasmas

- Flavors can be added by means of D7-branes, along 4d Minkowski and wrapped on non-compact 4-manifold.
- To account for vacuum polarization effects due to dynamical flavors , i.e. to go beyond the so-called quenched approximation , we need to account for the backreaction of the flavor branes on the background.
- Not an easy task if flavor branes are localized, on top of each other. Delta function sources and p.d.e.
- Most of the known results at finite T concern the quenched approximation where the flavor branes are treated as probes [Karch-Katz 02].

D3-D7 plasmas

Technology

- Take Nf >>1 D7-branes homogeneously smeared over transverse space. [F.B., Casero, Cotrone, Kiritsis, Paredes 05]

  This simplifies sugra:

  1) delta function sources → Ω density distribution 2-form

  2) partial diff. e.o.m → ordinary diff. e.o.m in a radial variable

  Preserve most of the isometries of unflavored background

- Consider a perturbative expansion in $\epsilon \sim \lambda N_f/N_c = g^2 N_f$. Up to second order this allows to find analytic solutions.
- D7 induce dilaton blow up: UV Landau pole. Decouple IR: cutoff $r_h \leq r < r^* \ll r_{LP}$, i.e. $T \ll \Lambda_{LP}$. Ensured taking $\epsilon \ll 1$

D3-D7 plasmas

Dual field theory. Example: D3-D7 in flat space.
Zi, i=1,2,3 complex transverse coordinates
Karch-Katz embedding for D7: Z1=0 (breaks SU(4)R)
Superpotential $W = \Phi_1[\Phi_2, \Phi_3] + \tilde{q}\Phi_1 q.$
N=4 → N=2 susy
Conformality broken at quantum level (massless flavors)
UV Landau Pole

Generalized embedding $\sum_1^3 a_i Z_i = 0, \quad \sum_1^3 |a_i|^2 = 1.$
Superpotential $W = \Phi_1[\Phi_2, \Phi_3] + \tilde{q}(a_1\Phi_1 + a_2\Phi_2 + a_3\Phi_3)q$

Smearing: Nf>>1 such terms, integrate over ai, recovers SU(3)x U(1), preserves N=1 susy. Flavor group is U(1)^(Nf)

D3-D7 plasmas

$$S = S_{IIB} + S_{fl}$$

$$S_{IIB} = \frac{1}{2\kappa_{10}^2}\int d^{10}x\sqrt{-g_{10}}\left[R - \frac{1}{2}\partial_M\Phi\partial^M\Phi - \frac{1}{2}e^{2\Phi}F_{(1)}^2 - \frac{1}{2}\frac{1}{5!}F_{(5)}^2\right]$$

$$S_{fl} = -T_7\sum_{N_f}\int_{\mathcal{M}_8} d^8\xi\, e^{\Phi}\sqrt{-\det\hat{g}_8} + T_7\sum_{N_f}\int_{\mathcal{M}_8}\hat{C}_8$$ (PDEs)

$$S_{fl}^{smear} = -T_7\int_{\mathcal{M}_{10}} d^{10}x\sqrt{-\det g_{10}}e^{\Phi}|\Omega| + T_7\int_{\mathcal{M}_{10}}\Omega\wedge C_8$$ (ODEs)

$$dF_{(1)} = -g_s\Omega$$

$$\Omega \equiv -g_s\sum_i \Omega^{(i)}, \quad |\Omega| \equiv \sum_i\sqrt{\frac{1}{2}\Omega^{(i)}_{MN}\Omega^{(i)}_{PQ}g^{MN}g^{PQ}}$$

D3-D7 plasmas

[X5 Sasaki-Einstein: $ds^2_{X_5} = ds^2_{KE} + (d\tau + A_{KE})^2, \quad dA_{KE} = 2J_{KE}$]

$$ds^2_{10} = h^{-\frac{1}{2}}\left[-b\,dt^2 + d\vec{x}_3^2\right] + h^{\frac{1}{2}}\left[S^8F^2b^{-1}\,dr^2 + r^2 ds_5^2\right]$$

$$h = \frac{R^4}{r^4}, \quad b = 1 - \frac{r_h^4}{r^4}$$

$$ds_5^2 = S^2 ds^2_{KE} + F^2(d\tau + A_{KE})^2, \quad dA_{KE} = 2J_{KE}$$

$$\Phi = \Phi(r), \quad F_{(5)} = Q_c\,(1 + *)\mathrm{vol}(X_5)$$

$$F_{(1)} = Q_f(d\tau + A_{KE}), \quad dF_{(1)} = 2Q_f J_{KE} \equiv -g_s\Omega$$

$$R^4 = \frac{Q_c}{4}, \quad Q_c = \frac{(2\pi)^4 g_s N_c\,\alpha'^2}{Vol(X_5)}, \quad Q_f = \frac{g_s N_f Vol(X_3)}{4Vol(X_5)}$$

D3-D7 plasmas

$$F = 1 - \frac{\epsilon_*}{24}\left(1 + \frac{2r^4 - r_h^4}{6r_*^4 - 3r_h^4}\right)$$

$$S = 1 + \frac{\epsilon_*}{24}\left(1 - \frac{2r^4 - r_h^4}{6r_*^4 - 3r_h^4}\right)$$

$$\Phi = \Phi_* + \epsilon_* \log \frac{r}{r_*}$$

$\epsilon \equiv Qf \exp(\Phi)$

D3-D7 plasmas

$$F = 1 - \frac{\epsilon_*}{24}(1 + \frac{2r^4 - r_h^4}{6r_*^4 - 3r_h^4}) + \frac{\epsilon_*^2}{1152}\left(17 - \frac{94}{9}\frac{2r^4 - r_h^4}{2r_*^4 - r_h^4} + \frac{5}{9}\frac{(2r^4 - r_h^4)^2}{(2r_*^4 - r_h^4)^2} + \right.$$
$$\left. -\frac{8}{9}\frac{r_h^8(r_*^4 - r^4)}{(2r_*^4 - r_h^4)^3} - 48\log(\frac{r}{r_*})\right) + O(\epsilon_*^3) \ ,$$

$$S = 1 + \frac{\epsilon_*}{24}(1 - \frac{2r^4 - r_h^4}{6r_*^4 - 3r_h^4}) + \frac{\epsilon_*^2}{1152}\left(9 - \frac{106}{9}\frac{2r^4 - r_h^4}{2r_*^4 - r_h^4} + \frac{5}{9}\frac{(2r^4 - r_h^4)^2}{(2r_*^4 - r_h^4)^2} + \right.$$
$$\left. -\frac{8}{9}\frac{r_h^8(r_*^4 - r^4)}{(2r_*^4 - r_h^4)^3} + 48\log(\frac{r}{r_*})\right) + O(\epsilon_*^3) \ ,$$

$$\Phi = \Phi_* + \epsilon_* \log\frac{r}{r_*} + \frac{\epsilon_*^2}{72}\left(1 - \frac{2r^4 - r_h^4}{2r_*^4 - r_h^4} + 12\log\frac{r}{r_*} + 36\log^2\frac{r}{r_*} + \right.$$
$$\left. + \frac{9}{2}\left(Li_2(1 - \frac{r_h^4}{r^4}) - Li_2(1 - \frac{r_h^4}{r_*^4})\right)\right) + O(\epsilon_*^3)$$

$$\Phi_* \equiv \Phi(r_*), \qquad Li_2(u) \equiv \sum_{n=1}^{\infty}\frac{u^n}{n^2}$$

D3-D7 plasmas

Focus on deep IR physics T<<Λ*<< ΛLP

$$
\begin{aligned}
F &= 1 - \frac{\epsilon_h}{24} + \frac{17}{1152}\epsilon_h^2 - \frac{\epsilon_h^2}{24}\log\frac{r}{r_h} \equiv F_h - \frac{\epsilon_h^2}{24}\log\frac{r}{r_h}\,, \\
S &= 1 + \frac{\epsilon_h}{24} + \frac{1}{128}\epsilon_h^2 + \frac{\epsilon_h^2}{24}\log\frac{r}{r_h} \equiv S_h + \frac{\epsilon_h^2}{24}\log\frac{r}{r_h}\,, \\
\Phi &= \Phi_h + \epsilon_h\log\frac{r}{r_h} + \frac{\epsilon_h^2}{6}\log\frac{r}{r_h} + \frac{\epsilon_h^2}{2}\log^2\frac{r}{r_h} + \frac{\epsilon_h^2}{16}Li_2\left(1 - \frac{r_h^4}{r^4}\right)
\end{aligned}
$$

$$
\epsilon_h = \epsilon_* + \epsilon_*^2\log\frac{r_h}{r_*}\,, \qquad T\frac{d\epsilon_h}{dT} = \epsilon_h^2
$$

D3-D7 plasmas

- Massless-flavored susy solution (b=1) exactly known . It has a dilaton blowing up at rLP (UV Landau pole) and a (good) singularity in the IR [Benini, Canoura, Cremonesi, Nunez, Ramallo 06].

- Non extremal solution is regular at the horizon

- D7-brane distribution dense enough if Nf>>1
- Regime of validity

  Nc>>1, λ>>1, Nf>>1, ϵ~λ Nf/Nc<<1

Thermodynamics

$$\epsilon_h \equiv \frac{\lambda_h Vol(X_3)}{16\pi\, Vol(X_5)} \frac{N_f}{N_c} \qquad\qquad \frac{d\epsilon_h}{dT} = \frac{\epsilon_h^2}{T} + O(\epsilon_h^3)$$

$$s = \frac{2\pi\ A_8}{\kappa_{(10)}^2\, V_3} = \frac{\pi^5}{2Vol(X_5)} N_c^2 T^3 \left[1 + \frac{1}{2}\epsilon_h + \frac{7}{24}\epsilon_h^2 + O(\epsilon_h^3)\right]$$

$$\varepsilon = \frac{E_{ADM}}{V_3} = \frac{3}{8}\frac{\pi^5}{Vol(X_5)} N_c^2 T^4 \left[1 + \frac{1}{2}\epsilon_h(T) + \frac{1}{3}\epsilon_h(T)^2 + O(\epsilon_h(T)^3)\right]$$

$$\frac{F}{V_3} \ = \ -p = \varepsilon - Ts = -\frac{1}{8}\frac{\pi^5}{Vol(X_5)} N_c^2 T^4 \left[1 + \frac{1}{2}\epsilon_h(T) + \frac{1}{6}\epsilon_h(T)^2 + O(\epsilon_h(T)^3)\right]$$

Check: first order results match with those obtained in the literature in the probe approximation [Mateos, Myers, Thomson 07]

Thermodynamics

Breaking of conformal invariance: a second order effect

Interaction measure (trace of stress energy tensor)

$$(\varepsilon - 3p)/T^4 = [\pi^5 N_c^2/16Vol(X_5)]\epsilon_h(T)^2$$

Speed of sound

$$v_s^2 = \frac{s}{c_V} = \frac{1}{3}\left[1 - \frac{1}{6}\epsilon_h(T)^2 + O(\epsilon_h(T)^3)\right]$$

Expect non zero bulk viscosity at second order

Hydrodynamics

- Effective theory of long wavelength fluctuations around local thermal equilibrium.
- Zero charge second order relativistic hydro

[Baier,Romatschke,Son,Starinets,Stephanov 2008; Romatschke 2009; Bhattacharyya, Hubeny, Minwalla, Rangamani 2008]

$$\nabla_\mu T^{\mu\nu} = 0 \qquad\qquad T^{\mu\nu} = \varepsilon u^\mu u^\nu + p\Delta^{\mu\nu} + \boxed{\pi^{\mu\nu} + \Delta^{\mu\nu}\Pi}$$

Dissipative terms

$$\varepsilon = \text{energy density}$$
$$u^\mu = \text{velocity field}$$
$$p(\varepsilon) = \text{pressure}$$
$$\Delta^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu$$
$$g^{\mu\nu} = \text{metric}$$

Hydrodynamics

$$T^{\mu\nu} = \varepsilon u^{\mu} u^{\nu} + p\Delta^{\mu\nu} + \pi^{\mu\nu} + \Delta^{\mu\nu}\Pi$$

Expansion in gradients of u^{μ} and $\varepsilon \longrightarrow s$ (via thermodynamics):

$$\begin{aligned}
\pi^{\mu\nu} \quad = \quad & -\eta\sigma^{\mu\nu} + \eta\tau_{\pi}\left[\langle D\sigma^{\mu\nu}\rangle + \frac{\nabla\cdot u}{3}\sigma^{\mu\nu}\right] + \kappa\left[R^{<\mu\nu>} - 2u_{\alpha}u_{\beta}R^{\alpha<\mu\nu>\beta}\right] \\
& +\lambda_1\sigma_{\lambda}^{<\mu}\sigma^{\nu>\lambda} + \lambda_2\sigma_{\lambda}^{<\mu}\Omega^{\nu>\lambda} + \lambda_3\Omega_{\lambda}^{<\mu}\Omega^{\nu>\lambda} + \kappa^{*}2u_{\alpha}u_{\beta}R^{\alpha<\mu\nu>\beta} \\
& +\eta\tau_{\pi}^{*}\frac{\nabla\cdot u}{3}\sigma^{\mu\nu} + \lambda_4\nabla^{<\mu}\log s\nabla^{\nu>}\log s
\end{aligned}$$

$$\begin{aligned}
\Pi \quad = \quad & -\zeta(\nabla\cdot u) + \zeta\tau_{\Pi}D(\nabla\cdot u) + \xi_1\sigma^{\mu\nu}\sigma_{\mu\nu} + \xi_2(\nabla\cdot u)^2 + \xi_3\Omega^{\mu\nu}\Omega_{\mu\nu} \\
& +\xi_4\nabla_{\mu}^{\perp}\log s\nabla_{\perp}^{\mu}\log s + \xi_5 R + \xi_6 u^{\alpha}u^{\beta}R_{\alpha\beta}
\end{aligned}$$

$\eta =$ shear viscosity, $\zeta =$ bulk viscosity, $\tau_{\pi}, \tau_{\Pi} =$ relaxation times.

Holographic calculations

Holographically:

- Each fluid mode has dual gravity mode.
- Fluctuate corresponding mode (gravity equations).
- Extract dispersion relations (for hydrodynamic modes).
- Correlators from basic AdS/CFT prescription:

$$\langle e^{-\int \phi_0 \mathcal{O}} \rangle = e^{-S_{gravity}(\phi_0)}$$

(extended to real time case).

Holographic calculations

Standard calculation of (some) coefficients.

Fluctuations $\sim e^{-i(\omega t - qz)} h_{(\cdot,\cdot)}$ $\Rightarrow$ modes classified by $SO(2)_{x,y}$.

From dispersion relation of scalar modes:

$$\omega = c_s q - i\Gamma q^2 + \frac{\Gamma}{c_s}\Big(c_s^2 \tau^{eff} - \frac{\Gamma}{2}\Big) q^3 + \mathcal{O}(q^4)$$

$$\Gamma = \frac{\eta}{sT}\left(\frac{2}{3} + \frac{\zeta}{2\eta}\right) \qquad \tau^{eff} = \frac{\tau_\pi + \frac{3\zeta}{4\eta}\tau_\Pi}{1 + \frac{3\zeta}{4\eta}}$$

From retarded correlator of tensorial mode:

$$G_R^{xy,xy} = p - i\eta\omega + \left(\eta\tau_\pi - \frac{\kappa}{2} + \kappa^*\right)\omega^2 - \frac{\kappa}{2} q^2 + \mathcal{O}(q^3, \omega^3)$$

Results [Bigazzi-Cotrone-Tarrio 2009]:

$$
\begin{aligned}
c_s &= \frac{1}{\sqrt{3}}\left(1 - \frac{1}{12}\epsilon_h^2\right) \\
\frac{\eta}{s} &= \frac{1}{4\pi} \qquad [\mathrm{Kovtun-Son-Starinets\ 2005}] \\
\frac{\zeta}{\eta} &= \frac{1}{9}\epsilon_h^2 \qquad \Rightarrow \quad \mathrm{Buchel's\ bound\ saturated\ at\ } \mathcal{O}(\epsilon_h^2).\ \mathrm{Small.} \\
\tau^{eff} T &= \tau_{\pi,0} T_0 + \frac{16-\pi^2}{128\pi}\epsilon_h^2 \qquad \Rightarrow \quad \mathrm{Positive\ correction\ (bound?).} \\
\frac{T\kappa}{s} &= \frac{T_0\kappa_0}{s_0}\left(1 - \frac{\epsilon_h^2}{8}\right) \qquad \Rightarrow \quad \mathrm{Negative\ correction\ (bound?).} \\
\frac{T^2}{p}(\kappa^* + \eta\tau_\pi) &= \frac{T_0^2}{p_0}\eta_0\tau_{\pi,0} + \frac{T_0^2}{p_0}\eta_0\left(\frac{\tau_{\pi,0}}{8} - \frac{16+\pi^2}{128\pi T_0}\right)\epsilon_h^2
\end{aligned}
$$

$$
\tau_{\pi,0} T_0 = \frac{2 - \log 2}{2\pi} \qquad \frac{T_0\kappa_0}{s_0} = \frac{1}{4\pi^2} \qquad \frac{T_0\eta_0}{p_0} = \frac{1}{\pi}
$$

Simpler derivation

5d reduction

$$S_5 = \frac{Vol(X_5)}{2\kappa_{10}^2} \int d^5x \sqrt{-\det g} \left[R[g] - \frac{40}{3}(\partial f)^2 - 20(\partial w)^2 - \frac{1}{2}(\partial \Phi)^2 - V(\Phi, f, w) \right]$$

$$V(\Phi, f, w) = 4e^{\frac{16}{3}f + 2w}\left(e^{10w} - 6 + Q_f e^{\Phi}\right) + \frac{1}{2}Q_f^2 e^{\frac{16}{3}f - 8w + 2\Phi} + \frac{Q_c^2}{2}e^{\frac{40}{3}f}$$

AdS vacuum at Qf=0 (i.e. ϵh=0): f=w=Φ=0. Fluctuating around:

$$\begin{array}{lllll} f & \leftrightarrow & \Delta = 8 & \Rightarrow & \text{Irrelevant.} \\ w & \leftrightarrow & \Delta = 6 & \Rightarrow & \text{Irrelevant.} \\ \Phi & \leftrightarrow & \Delta = 4 & \Rightarrow & \text{Marginally irrelevant.} \end{array}$$

Φ Breaks conformality at leading order (dual to flavor term in superpotential)

Simpler derivation

- At leading order only Φ contributes

V~ -12 + 4 Qf exp(Φ) + O(ϵh^2)

$$\mathcal{V}_\phi \equiv \left(\frac{V'(\phi_h)}{V(\phi_h)}\right)^2 \qquad\qquad \mathcal{V}_{f,w} = 0\,, \quad \mathcal{V}_\Phi = \frac{\epsilon_h^2}{9}$$

- Note: T d(ϵh^2)/dT = O(ϵh^3) i.e. it is a constant in our limits
- System effectively 5d gravity plus single scalar with exponential potential V=Vo e^(a Φ) [Chamblin-Reall model]
- For these models first order hydro coefficients simply given in terms of the potential [Gubser,Pufu,Rocha 2008]

$$\frac{\zeta}{\eta} = \frac{V'(\phi_h)^2}{V(\phi_h)^2} = \frac{\epsilon_h^2}{9}\,. \qquad\qquad c_s^2 - \frac{1}{3} = -\frac{1}{2}\frac{V'(\phi_h)^2}{V(\phi_h)^2} = -\epsilon_h^2/18$$

Simpler derivation

- In [Kanitscheider-Skenderis 2009]: Chamblin-Reall models

$$S = \frac{1}{2\kappa^2} \int d^5x \sqrt{-\det g} \left[R[g] - \frac{1}{2}(\partial\phi)^2 - V_0 e^{\gamma\phi} \right]$$

- Can be obtained from toroidal compactifications of pure gravity+cosmo constant in 2σ+1 dimensions and continuation in σ!
- $Cs^2 = 1/3 - \gamma^2/2$ = (higher dim CFT) = $1/(2\sigma-1)$
- For D3-D7, $\sigma = 2 + \epsilon h^2/4 + O(\epsilon h^3)$
- Crucial point: everything smooth in σ in 5d
- From known hydrodynamics on $AdS_{2\sigma+1}$ obtain hydro by dimensional reduction

[Romatschke 2009, Bigazzi, Cotrone, to appear]

All the transport coefficients :

[Kovtun-Son-Starinets 05]

$$\delta \equiv (1-3c_s^2) = \frac{\epsilon_h^2}{6}$$

$$\boxed{\frac{\eta}{s} = \frac{1}{4\pi}} \qquad \boxed{T\tau_\pi = \frac{2-\log 2}{2\pi} + \frac{3(16-\pi^2)}{64\pi}\delta} \qquad \frac{T\kappa}{s} = \frac{1}{4\pi^2}\left(1-\frac{3}{4}\delta\right)$$

$$\frac{T\lambda_1}{s} = \frac{1}{8\pi^2}\left(1+\frac{3}{4}\delta\right) \qquad \frac{T\lambda_2}{s} = -\frac{1}{4\pi^2}\left(\log 2 + \frac{3\pi^2}{32}\delta\right) \qquad \frac{T\lambda_3}{s} = 0$$

$$\frac{T\lambda_4}{s} = 0 \qquad \frac{T\kappa^*}{s} = -\frac{3}{8\pi^2}\delta \qquad T\tau_\pi^* = -\frac{2-\log 2}{2\pi}\delta$$

$$\boxed{\frac{\zeta}{\eta} = \frac{2}{3}\delta} \qquad \boxed{T\tau_\Pi = \frac{2-\log 2}{2\pi}} \qquad \frac{T\xi_1}{s} = \frac{1}{24\pi^2}\delta$$

$$\frac{T\xi_2}{s} = \frac{2-\log 2}{36\pi^2}\delta \qquad \frac{T\xi_3}{s} = \frac{T\xi_4}{s} = 0 \qquad \frac{T\xi_5}{s} = \frac{1}{12\pi^2}\delta \qquad \frac{T\xi_6}{s} = \frac{1}{4\pi^2}\delta$$

[Saturation of Buchel's bound]

Summarizing

- Dual of a theory with conformality broken by marginally irrelevant operators (flavor terms) behaves effectively, at leading order, like a Chamblin-Reall model.
- Transport coefficients from [Kanitscheider-Skenderis 2009]
- Same holds for marginally relevant operators (e.g. cascading plasmas)

Generalizations

- QGP (RHIC, LHC)nearly conformal and strongly coupled for $1.5T_c \lesssim T \lesssim 4T_c$.
- Model it holographically with AdS5 (BH) deformed by a scalar dual to marginally relevant operator
- Use previous relations and estimate all the transport coefficients (to second order) at RHIC and LHC: just one parameter to fit, for example the speed of sound (for which we have quite solid lattice estimates)

Estimates for QCD

- From lattice [Katz 2005]: $c_s^2(T \sim 1.5T_c) \sim$ 0.283 (RHIC)

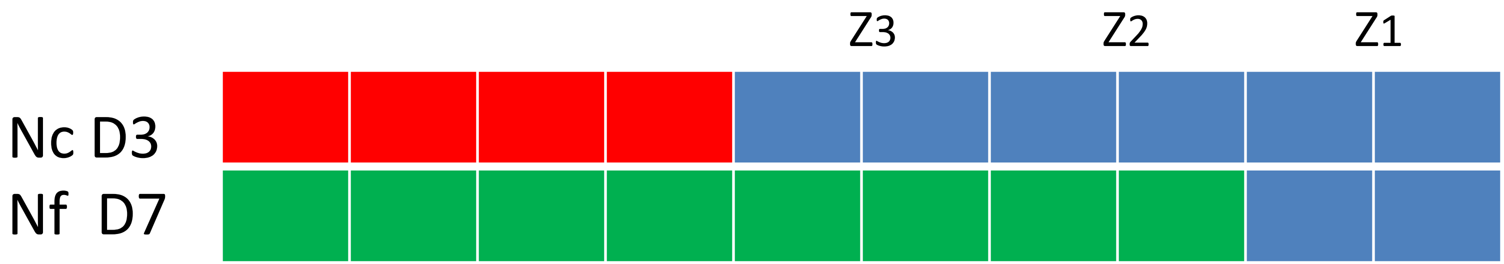
$\frac{\eta}{s}$	$\frac{1}{4\pi}$	$T\tau_\pi$	0.222	$\frac{T\kappa}{s}$	0.022
$\frac{T\lambda_1}{s}$	0.014	$\frac{T\lambda_2}{s}$	-0.021	$\frac{T\lambda_3}{s}$	0
$\frac{T\kappa^*}{s}$	-0.006	$T\tau_\pi^*$	-0.031	$\frac{T\lambda_4}{s}$	0
$\frac{\zeta}{\eta}$	0.101	$T\tau_\Pi$	0.208	$\frac{T\xi_1}{s}$	0.001
$\frac{T\xi_2}{s}$	0.001	$\frac{T\xi_3}{s}$	0	$\frac{T\xi_4}{s}$	0
$\frac{T\xi_5}{s}$	0.001	$\frac{T\xi_6}{s}$	0.004		

Comments and future directions

- Studied jet quenching parameter (flavors enhance it)
- Equations extended to massive flavors
- Study of probes on these backgrounds and conductivity
- Finite baryon density (work in progress)
- Condensed matter applications
- Non-relativistic limits

Thank you

Simplest example: Nc D3 + Nf D7 in flat space ($X_5=S^5$) at T=0



- At Nf=0 a SCFT: $\mathcal{N}$=4 SU(Nc) SYM (SU(4)R). In $\mathcal{N}$=1 components:

$$W_0 = \Phi_1[\Phi_2, \Phi_3] \qquad SU(3) \times U(1)_R \text{ symmetry}$$

- Add Nf D7-branes wrapping non compact 4manif (ex. $Z_1 = \mu_1$)
  D3-D7 strings↔ fundamental hypers. SU(Nf) flavor symmetry

$$W_2 = W_0 + \tilde{q}_i(\Phi_1 - m_1)q_i$$

Break global symmetry, conformal invariance and susy
$\mathcal{N}$=4 → $\mathcal{N}$=2 , b0 = (3Nc - 3Nc) - Nf → UV Landau pole

We will consider $\mathcal{N}$=1 setups. They will inherit this UV behavior.
We will focus on IR physics well below the Landau Pole.

The smearing

Take Nf>>1 D7-branes homogeneously smeared over transverse space. Preserve original global symmetries and $\mathcal{N}$=1 susy (at T=0).

Generalized embedding $\sum_{i=1}^{3} a_i Z_i = \mu\,, \quad \sum_{i=1}^{3} |a_i|^2 = 1$

$$W = \Phi_1[\Phi_2, \Phi_3] + \tilde{q}(a_1\Phi_1 + a_2\Phi_2 + a_3\Phi_3 - m)q$$

Smearing= sum over flavors, integrate over ai in W. Recover SU(3).

Flavor symmetry explicitly broken to U(1)^Nf .

Let's focus on massless case m=0 (i.e. μ=0): D7 reach the origin.

Massless susy embeddings also solve D7 worldvolume equations in non-extremal case.

Transport coefficients of AdS_6:

[Bhattacharyya-Loganayagam-Mandal-Minwalla-Sharma 2008]

$$
\begin{aligned}
\eta^{(2\tilde{\sigma})} &= \frac{s^{(2\tilde{\sigma})}}{4\pi} \\
\kappa^{(2\tilde{\sigma})} &= \frac{2\eta^{(2\tilde{\sigma})}2\tilde{\sigma}}{4\pi T(2\tilde{\sigma}-2)} \\
\tau_\pi^{(2\tilde{\sigma})} &= \frac{2\tilde{\sigma}}{4\pi T}\left(1-\int_1^\infty \frac{y^{2\tilde{\sigma}-2}-1}{y(y^{2\tilde{\sigma}}-1)}dy\right) \\
\lambda_1^{(2\tilde{\sigma})} &= \frac{\eta^{(2\tilde{\sigma})}2\tilde{\sigma}}{8\pi T} \\
\lambda_2^{(2\tilde{\sigma})} &= -\frac{2\eta^{(2\tilde{\sigma})}2\tilde{\sigma}}{4\pi T}\int_1^\infty \frac{y^{2\tilde{\sigma}-2}-1}{y(y^{2\tilde{\sigma}}-1)}dy \\
\lambda_3^{(2\tilde{\sigma})} &= 0
\end{aligned}
$$

Jet quenching parameter

Observed medium-induced suppression of back-to-back high-p_T jets, at RHIC. Due to radiative energy loss of relativistic partons moving through the plasma.

Energy loss characterized by jet quenching parameter

$$\hat{q} = \frac{(\text{energy transf. from the plasma})^2}{\text{mean free path}}$$

Non perturbative definition in terms of a certain light-like Wilson loop. Evaluated in dual gravity setup [Liu, Rajagopal, Wiedemann 06]

$$\hat{q} = \frac{\pi^3 \sqrt{\lambda_h}\,\Gamma(\frac{3}{4})}{\sqrt{Vol(X_5)}\,\Gamma(\frac{5}{4})} T^3 \left[1 + \frac{1}{8}(2+\pi)\epsilon_h + \gamma\,\epsilon_h^2 + O(\epsilon_h^3)\right]$$

$$\gamma \approx 0.5565$$

Flavors enhance the jet quenching.

Opposite in pQCD [Muller-Nagle 2006]