Recent Progress in Applying Gauge/Gravity Duality to Quark-Gluon Plasma & Nuclear Physics

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"Holography"
what is it?

Part I: “Top-Down”

Holography = Solvable Toy Models of Strong coupling dynamics.

(Part II: “Bottom-up”: Can QCD be modeled using holographic ideas?)

Holography = Solvable Toy Model

Solvable models of strong coupling dynamics.

- Study Transport, real time
- Study Finite Density
- Explore paradigms "beyond Landau"

(Challenging in real QCD, experimentally relevant)

(this is interesting for a different audience)

Gives us qualitative guidance/intuition.

Not QCD! Expect errors of order 100%

(better than extrapolating perturbation theory to $\alpha_s \sim 1$??)

Holographic Theories:

Examples known:

- in d=1, 2, 3, 4, 5, 6 space-time dimensions
- with our without super-symmetry
- conformal or confining
- with or without chiral symmetry breaking
- with finite temperature and density

Holographic Theories:

Holographic toy models have two key properties:

"Large N": theory is essentially classical

"Large λ": large separation of scales in the spectrum

$$m_{\text{spin-2-meson}} \sim \lambda^{1/4} \, m_{\text{spin-1-meson}}$$

QCD: **1275 MeV** **775 MeV**

(note: there are some exotic examples where the same parameter N controls both, classicality and separation of scales in spectrum)

Successes and recent developments

- Viscosity and Hydrodynamics
- Energy Loss
- Thermalization

Viscosity and Hydrodynamics

Viscosity

Viscosity can be quantified:

water: 1 centipoise (cp)
air: 0.02 cp
honey: 2000-10000 cp

(1 cp = 10^{-2} P = 10^{-3} Pa·s)

Measuring Viscosity - an example

Pitch drop experiment

Started in 1930

8 drops fell so far

but no one has ever witnessed a drop fall

2005 Ig Nobel Prize in Physics

Viscosity of pitch: 230 billions times that of water

($2.3\ 10^{11}$cp)

Measuring Viscosity - an example

Recall: Viscosity of pitch: ~ 2.3 10^{11}cp

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RHIC's measurement of QGP (confirmed by LHC):

$$\eta \sim \frac{\hbar}{4\pi} s \sim \frac{10^{-27}\,\mathrm{erg}\cdot\mathrm{s}}{(10^{-13}\,\mathrm{cm})^3} \sim 10^{14}\,\mathrm{cp}$$

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BNL press release 2005:

"The degree of collective interaction, rapid thermalization, and extremely low viscosity of the matter being form at RHIC makes this the most nearly perfect liquid ever observed."

Viscosity in Holography:

In a large class of systems:

$$\frac{\eta}{s} = \frac{\hbar}{4\pi}$$ (KSS)

- pinpoints correct observable
- in contrast to QGP, η/s enormous for pitch
- gives ball-park figure
- large at weak coupling: bound?

Viscosity – Recent Developments

Not a bound! (Kats, Petrov, 2007)

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 - \frac{1}{2N}\right)$$

$\mathcal{N} = 2$ Sp(N)
4 fundamental
1 antisymmetric traceless

Higher Curvature corrections violate bound.

(Brigante, Liu, Myers, Shenker, Yaida, Buchel, Sinha, ….)

Calculations only reliable if violations are small.

Hydro – Recent Developments

Viscosity is not the only hydro transport coefficient that can be calculated holographically.

- 2^{nd} order hydro
  - Calculated in 2007 (Romatschke et. al., Batthacharyya et. al.)
  - Needed for stable hydro simulation (causality!)
  - Holographic values/structure routinely used
- anomalous transport

Anomalous Transport in Hydro

(following Kharzeev and Son)

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

Anomalous Transport in Hydro

(following Kharzeev and Son)

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB) 2\mu\vec{\omega}]$$

J: conserved current

1) Baryon Number or

2) Electric Charge

Anomalous Transport in Hydro

(following Kharzeev and Son)

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}\left[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}\right]$$

B: magnetic field
“Chiral Magnetic Effect”

Anomalous Transport in Hydro

(following Kharzeev and Son)

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

ω: vorticity (= curl of velocity)
"Chiral Vortical Effect"

Anomalous Transport in Hydro

(following Kharzeev and Son)

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

axial chemical potential
(requires non-zero axial charge)

$$\langle \mu_5 \rangle = 0$$

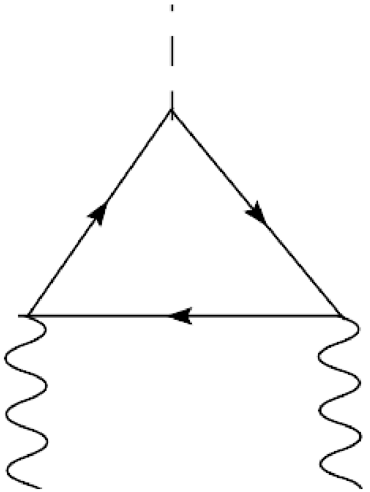
$$\langle {\mu_5}^2 \rangle \neq 0$$

relies on event
by event fluctuations

Anomalous Transport in Hydro

(following Kharzeev and Son)

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}\left[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}\right]$$



Coefficients determined by anomaly!

Relative size of baryon versus charge asymmetry unambiguous.

Anomaly and the CVE

connection between CME and anomaly was quantitatively understood before (Kharzeev, …)

How does the anomaly know about vorticity?

Erdmenger et. al, Banerje et. al:

In holographic models CVE completely determined in terms of

Chern-Simons term = anomaly.

Anomaly and the CVE

How does the anomaly know about vorticity?

Son, Surowka: True in general.

axial anomaly in background electromagnetic fields

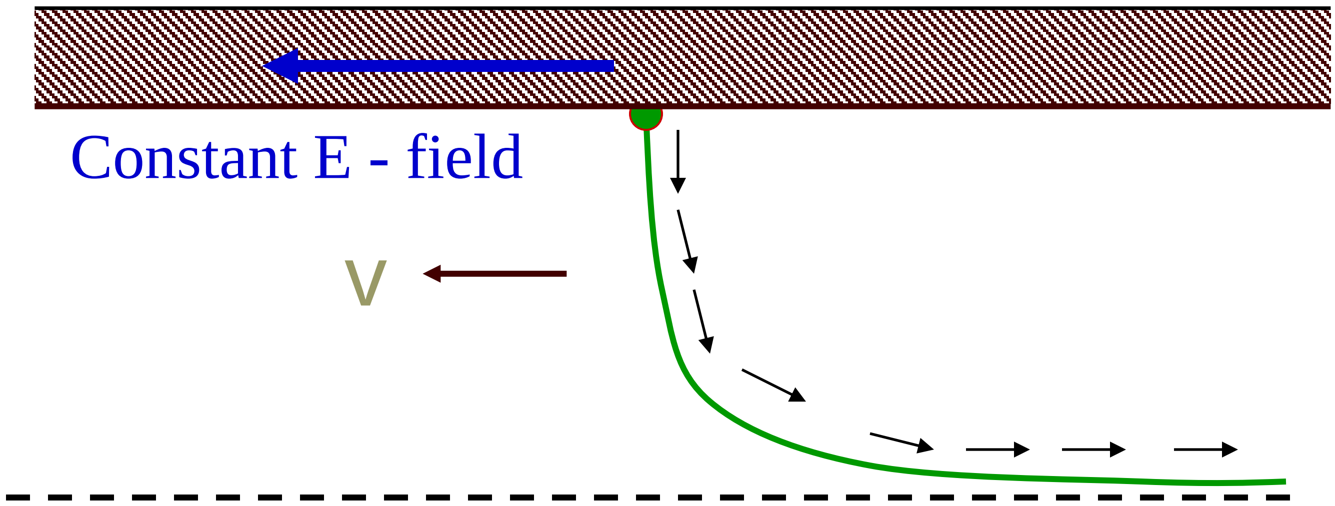
+

entropy current with non-negative divergence

= CVE

Energy Loss

Energy Loss (2006): Heavy quarks

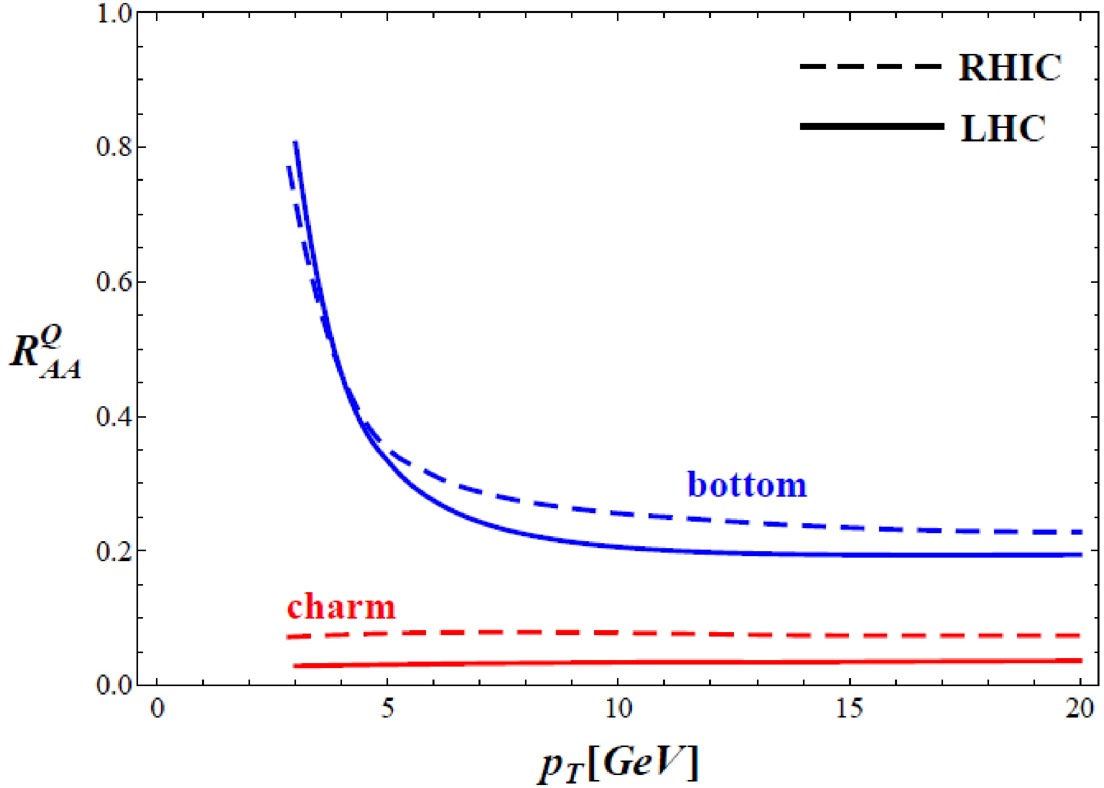


$$\frac{dp}{dt} = -\mu\, p \qquad \mu = \pi T\, \frac{\Delta m(T)}{m} \qquad \Delta m(T) \equiv \tfrac{1}{2}\sqrt{\lambda}T$$

(Casalderrey-Solana & Teaney, HKKKY, Gubser)

Energy Loss, Recent Developments:

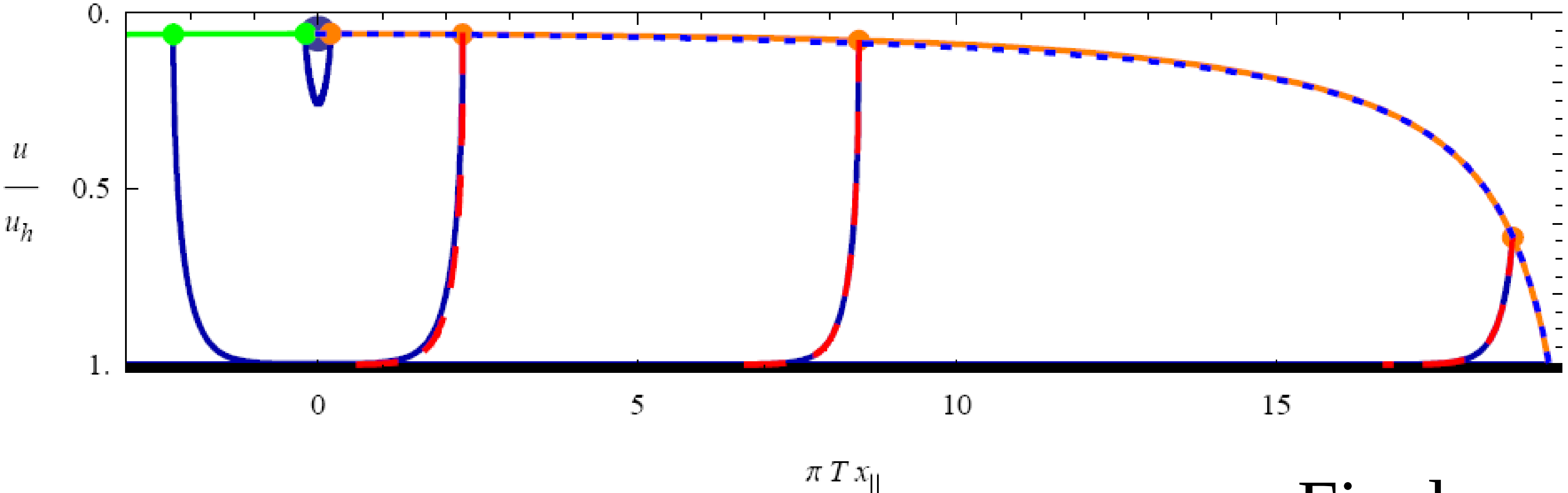
Use holographic models to make LHC "predictions":



(Ficnar, Noronha, Gyulassy)

Energy Loss, Light Quarks (2010)

(Chesler, Jensen, AK, Yaffe; Gubser, Gulotta, Pufu, Rocha)

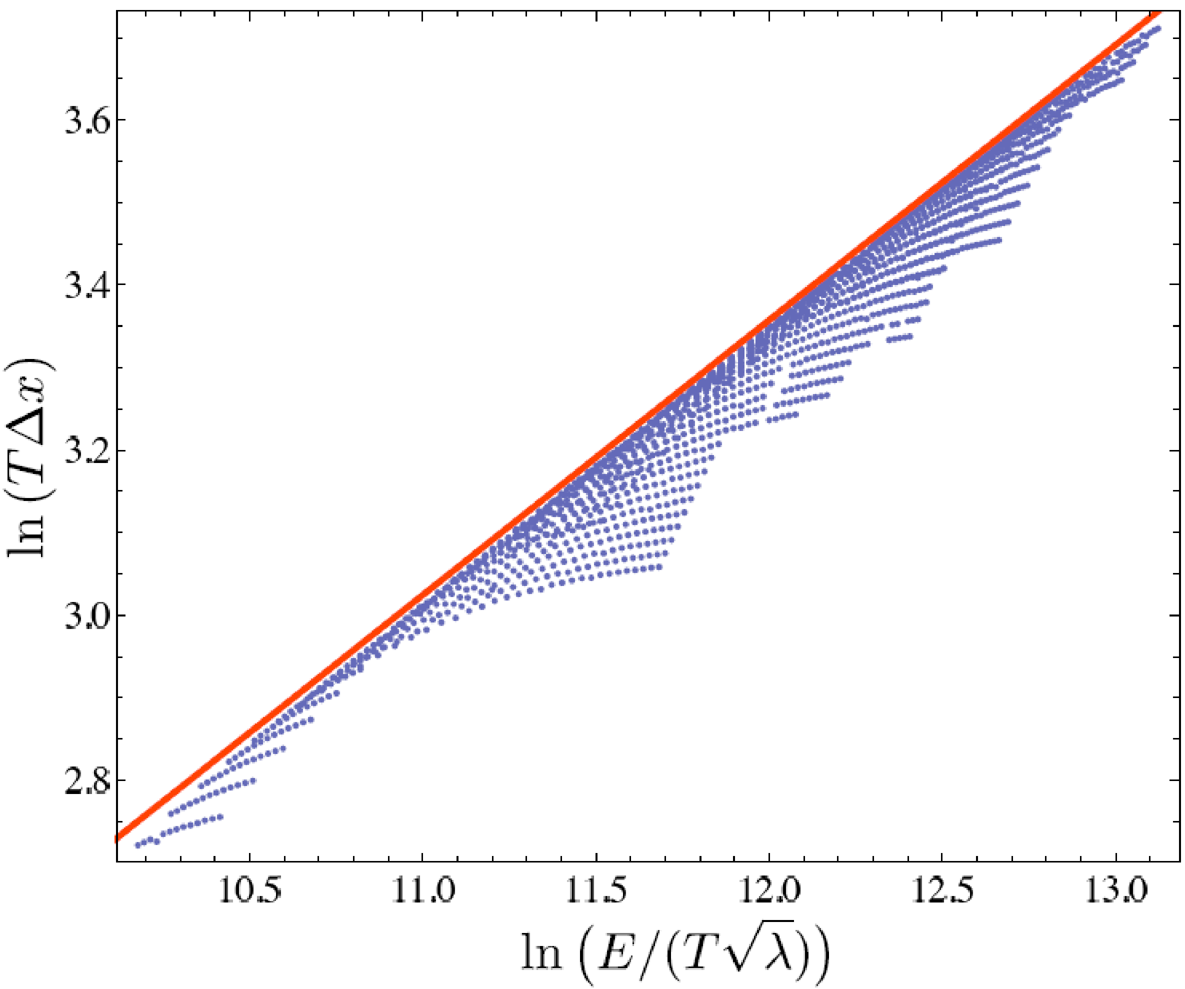


Zero T Jets

Quasiparticle in Plasma (for E >> T)

Final Diffusion

Stopping Distance vs Energy



(Chesler, Jensen, AK, Yaffe)

Stopping Distance:

Perturbative QCD: **$L \sim E^{1/2}$** (BDMPS, …)

Holography:

Maximal Stopping Distance: **$L \sim E^{1/3}$**

Typical Stopping Distance: **$L \sim E^{1/4}$**

(Arnold, Vaman - 2011)

Experiment: **1/3 preferred over 1/2 ???**

Stopping Distance: **Exponents!**

Perturbative QCD: **$L \sim E^{1/2}$** (BDMPS, …)

Holography:

Maximal Stopping Distance: **$L \sim E^{1/3}$**

Typical Stopping Distance: **$L \sim E^{1/4}$**

(Arnold, Vaman - 2011)

Experiment: **1/3 preferred over 1/2 ???**

Recent Data:

It is my understanding that recent data points towards "perturbative" mechanisms for high energy jets.

Question: is there some window of energies in which holographic models are valid?

Thermalization

Why does the QCD fireball thermalize so rapidly?

Thermalization

Why does the QCD fireball thermalize so rapidly?

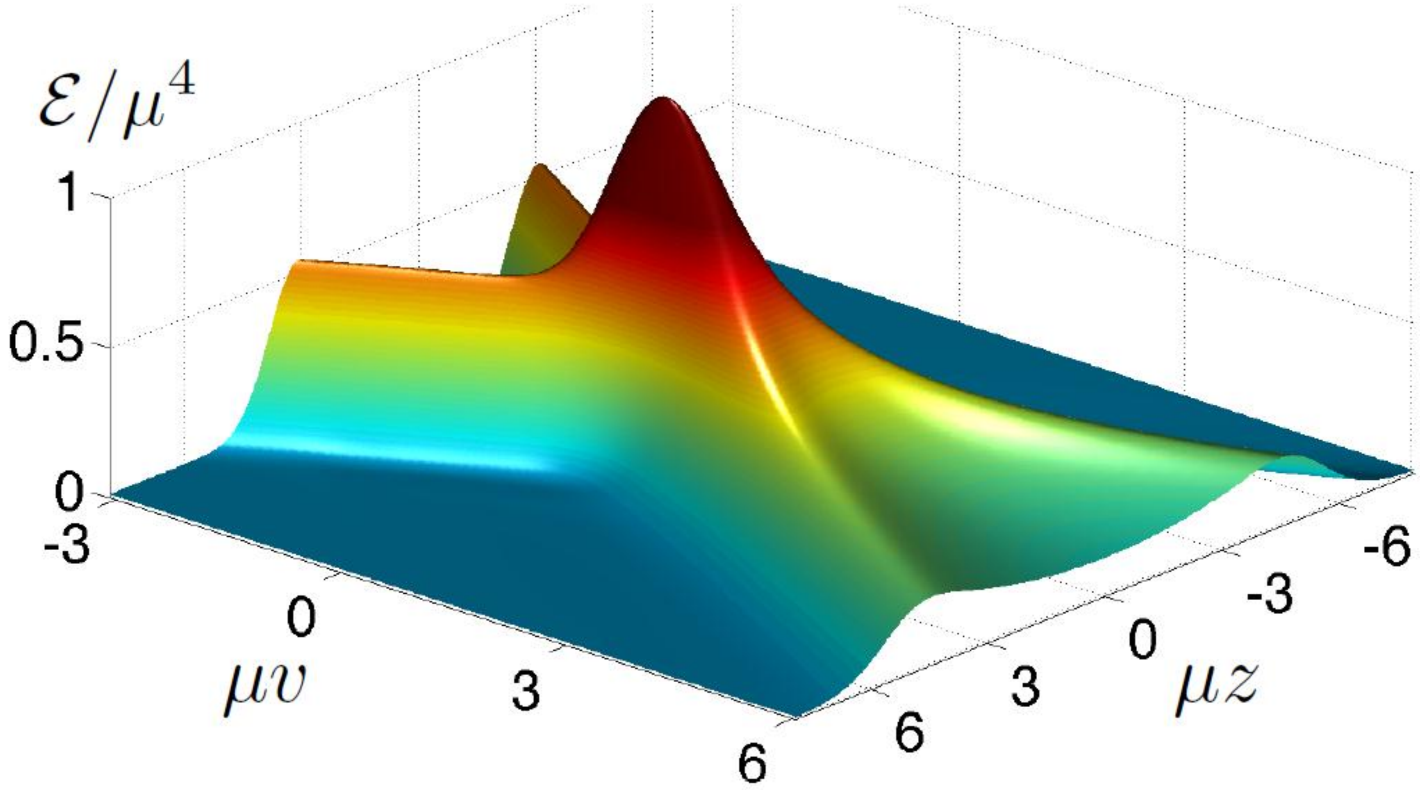
too hard!

Thermalization

How quickly does the holographic fireball thermalize?

Shockwave-collision to black hole

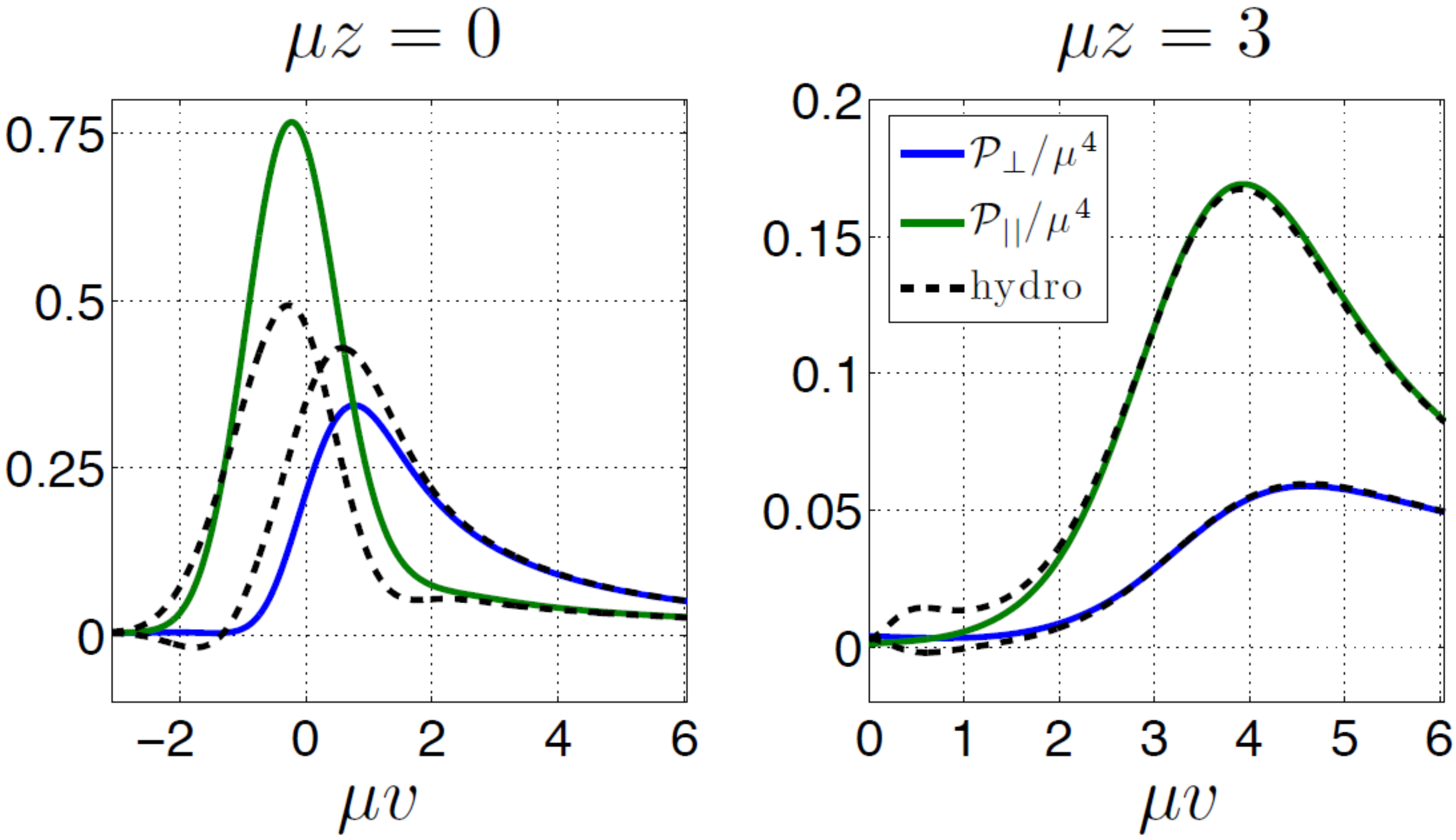
(Chesler, Yaffe)



Energy/area in shock ~ μ^3

Shockwave-collision to black hole

(Chesler, Yaffe)



Shockwave-collision to black hole

(Chesler, Yaffe)

"RHIC":

$\mu \sim 2.3$ GeV

Hydro valid ~ 0.35 fm/c << 1 fm/c

But: there is so much more info in this plot!

What do you want to know?

Summary: recent progress

- Viscosity and Hydrodynamics
- Energy Loss
- Thermalization

Part II: “Bottom-Up”

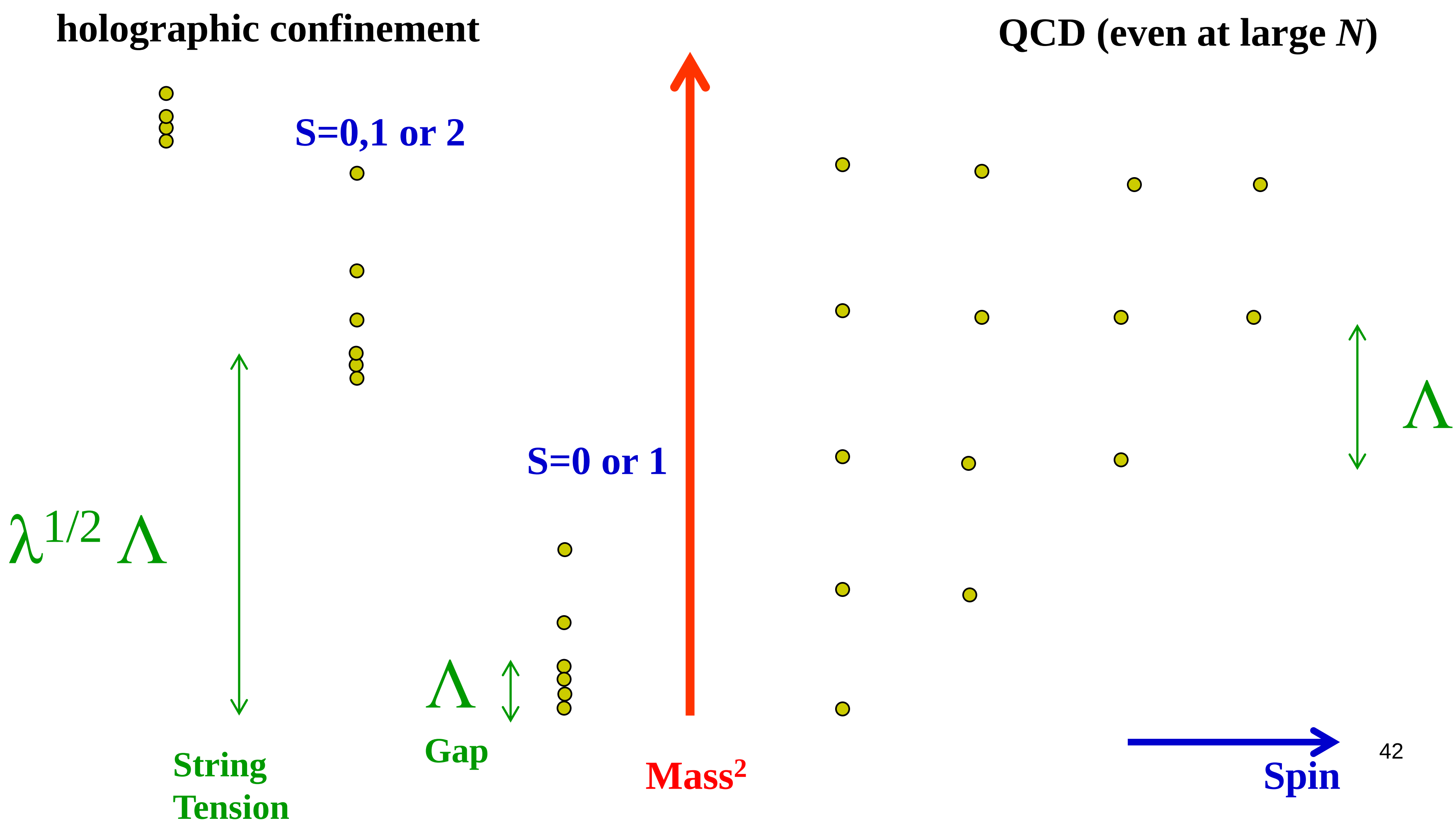
Can QCD be modeled using holographic ideas?

(work with Carlos Hoyos and Raul Alvares ; 1108.1191)

Bottom-up Strategy

- Postulate an effective theory for QCD in terms of a 5d bulk (2-derivative action.)
- Follow **standard holography rules** to fix action and background (comparing to UV free QCD)
- Model is justified by success.
- Systematic expansion relies on 5 >> 3. How good is this approximation?

Bottom-up versus top down:



Bottom-Up Success. (Erlich, Katz, Son, Stephanov)

TABLE II: Results of the model for QCD observables. Model A is a fit of the three model parameters to m_π, f_π and m_ρ (see asterisks). Model B is a fit to all seven observables.

Observable	Measured (MeV)	Model A (MeV)	Model B (MeV)
m_π	139.6±0.0004 [8]	139.6*	141
m_ρ	775.8±0.5 [8]	775.8*	832
m_{a_1}	1230±40 [8]	1363	1220
f_π	92.4±0.35 [8]	92.4*	84.0
$F_\rho^{1/2}$	345±8 [15]	329	353
$F_{a_1}^{1/2}$	433±13 [6, 16]	486	440
$g_{\rho\pi\pi}$	6.03±0.07 [8]	4.48	5.29

Accident?

Bottom-up Motivation

- Even if bottom-up gave only $1/3^2 \sim 10\%$ errors (highly questionable), it would never be competitive with lattice for masses + equilibrium. Why bother?
- Answers are simple and intuitive.
- Can be used to quickly survey large classes of non-QCD theories (e.g. for technicolor or hidden valleys).

Holographic rules:

Holography - Rule 1:

Field theory operator ↔ Bulk field

Implies infinite number of bulk fields, one for each QCD operator:

$$\overline{\psi}\,\psi\,,\ \ \overline{\psi}\,\gamma_\mu\psi\,,\ \ \overline{\psi}\,\gamma_{[\mu}\gamma_{\nu]}\psi\,,\ \ \overline{\psi}\,F_{\mu\nu}\psi\,,\ \ \ldots$$

Holographic Mesons:

(Erlich, Katz, Son, Stephanov; Karch, Katz, Son, Stephanov)

$$\overline{\psi}\,\psi \longrightarrow X$$

$$\overline{\psi}\,\gamma_\mu\psi \longrightarrow A_\mu$$

Dimension 3

$$S = \int d^5x\,\sqrt{g}\;\mathrm{Tr}\left\{|DX|^2 + 3|X|^2 - \frac{1}{4g_5^2}(F_L^2 + F_R^2)\right\}$$

Drop all fields dual to operators of dimension 4 and higher!
(and hope for the best).

Holographic rules:

Holography - Rule 2:

Correlation functions $\leftrightarrow$ Bulk on shell action

Large momentum behavior of bulk propagator (plugged into action) has to reproduce free UV correlators of QCD.

Hard and Soft Wall Models:

(Erlich, Katz, Son, Stephanov; Karch, Katz, Son, Stephanov)

$$S = \int d^5x \sqrt{g}\ \mathrm{Tr}\left\{ |DX|^2 + 3|X|^2 - \frac{1}{4g_5^2}(F_L^2 + F_R^2) \right\}$$

↑

fixed by UV behavior of JJ correlator

Guess background geometry

hard wall: simple
soft wall: correct Regge

} **AdS in UV**

Building a better model.

What about:

$\overline{\psi} F_{\mu\nu}\psi$ $\longrightarrow$ **Dimension 5. Can be neglected?**
(dimension ~ $\lambda^{1/4}$ in holography)

$\overline{\psi}\gamma_{[\mu}\gamma_{\nu]}\psi$ $\longrightarrow$ **Dimension 3. Massive $B_{\mu\nu}$ should definitely be included.**
(dimension ~ $\lambda^{1/4}$ in holography)

Without $B_{\mu\nu}$ operator, we are missing "half" of the vector mesons ($J^{PC} = 1^{+-}$) - does it matter?

Hard- and Softwall predict: no b_1!

$b_1(1235)$ $\quad I^G(J^{PC}) = 1^+(1^{+-})$

Mass $m = 1229.5 \pm 3.2$ MeV $\quad (S = 1.6)$
Full width $\Gamma = 142 \pm 9$ MeV $\quad (S = 1.2)$

$b_1(1235)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\omega\pi$	dominant		348
$[D/S$ amplitude ratio $= 0.277 \pm 0.027]$			
$\pi^{\pm}\gamma$	$(1.6\pm0.4) \times 10^{-3}$		607
$\eta\rho$	seen		†
$\pi^+\pi^+\pi^-\pi^0$	< 50 %	84%	535
$(K\overline{K})^{\pm}\pi^0$	< 8 %	90%	248
$K^0_S K^0_L \pi^{\pm}$	< 6 %	90%	235
$K^0_S K^0_S \pi^{\pm}$	< 2 %	90%	235
$\phi\pi$	< 1.5 %	84%	147

Is the b_1 parametrically heavy?

LIGHT UNFLAVORED
$(S = C = B = 0)$

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^{\pm}$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(600)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(1950)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $a_2(1320)$	$1^-(2^{++})$	• $f_2(2010)$	$0^+(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$	$f_0(2020)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $a_4(2040)$	$1^-(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	• $f_4(2050)$	$0^+(4^{++})$

Let’s look at PDG!

Is the b_1 parametrically heavy?

LIGHT UNFLAVORED ($S = C = B = 0$)	$I^G(J^{PC})$		$I^G(J^{PC})$
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• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• ~~$f_2(1270)$~~	~~$0^+(2^{++})$~~	$\rho(1900)$	$1^+(1^{--})$
• ~~$f_1(1285)$~~	~~$0^+(1^{++})$~~	$f_2(1910)$	$0^+(2^{++})$
• ~~$\eta(1295)$~~	~~$0^+(0^{-+})$~~	• $f_2(1950)$	$0^+(2^{++})$
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• $\pi_1(1400)$	$1^-(1^{-+})$	• $f_4(2050)$	$0^+(4^{++})$

Isospin singlets mix with glue sector (need extra scalar fields).

Should not expect agreement.

Is the b_1 parametrically heavy?

	$I^G(J^{PC})$
$\pi^\pm$	$1^-(0^-)$
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Included in Hard/Soft wall model

Is the b$_1$ parametrically heavy?

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Spin 0 or 2 mesons – need extra fields; Do not mix -- not important for understanding vectors + pions.

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	$I^G(J^{PC})$
$\pi^{\pm}$	$1^-(0^-)$
π^0	$1^-(0^{-+})$
$\rho(770)$	$1^+(1^{--})$
$b_1(1235)$	$1^+(1^{+-})$
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$\pi_1(1400)$	$1^-(1^{-+})$

Created by dimension 5 operator:

$$\overline{\psi} F_{\mu\nu} \gamma_5 \psi$$

5 >> 3 implies: 1400 MeV "much" heavier than 1260 MeV

Is the b_1 parametrically heavy?

	$I^G(J^{PC})$
$\pi^{\pm}$	$1^-(0^-)$
π^0	$1^-(0^{-+})$
$\rho(770)$	$1^+(1^{--})$
$b_1(1235)$	$1^+(1^{+-})$
$a_1(1260)$	$1^-(1^{++})$

But dropping the dimension 3 operator

$$\overline{\psi}\,\gamma_{[\mu}\gamma_{\nu]}\psi$$

is surely incompatible with data!!!

Including the new field:

Bi-fundamental $B_{\mu\nu}$ -- complex field.

What is the role of real and imaginary part?

Recall: bi-fundamental, complex X dual to

$$\bar{\psi}\psi + i\bar{\psi}\gamma_5\psi$$

So: $B_{\mu\nu}$ dual to:

$$\bar{\psi}\gamma_{[\mu}\gamma_{v]}\psi + i\bar{\psi}\gamma_5\gamma_{[\mu}\gamma_{v]}\psi$$

But…..

$B_{\mu\nu}$ dual to: $\bar{\psi}\gamma_{[\mu}\gamma_{\nu]}\psi + i\bar{\psi}\gamma_5\gamma_{[\mu}\gamma_{\nu]}\psi$

$$\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi = \frac{i}{2}\epsilon^{\mu\nu}{}_{\alpha\beta}\bar{\psi}\sigma^{\alpha\beta}\psi.$$

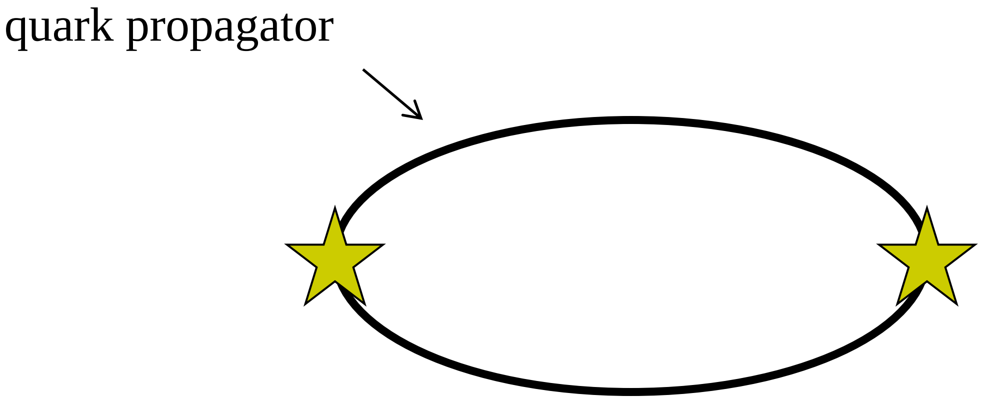
$B_{\mu\upsilon}$ is an imaginary anti-self dual field!

(can be dealt with)

(Domokos, Harvey, Royston)

Fix Parameters by match to QCD.

in the UV: 1-loop!



$$\star = \begin{cases} V^{\mu\, a}(x) = \bar{\psi}(x)\gamma^{\mu}\tau^{a}\,\psi(x) \\ \\ T^{\mu\nu\, a}(x) = \bar{\psi}(x)\sigma^{\mu\nu}\tau^{a}\,\psi(x) \end{cases}$$

Holographic matching.

4 coefficients in large q correlators

3 coupling constants in bulk action.

All couplings fixed + 1 consistency check.

Prediction: **masses and couplings of 1^{+-} mesons**

But: **will also shift the masses of vector mesons**

Caveat:

We are still guessing the geometry!

Our results refer to hard wall model only.

Results:

Meson spectrum doesn't work!

Main problem: typically b_1 wants to be lighter than ρ.

If we squeeze parameters we can force:

$$m_\rho \simeq 753.95 \text{ MeV}, \; m_{a_1} \simeq 1238.24 \text{ MeV and } m_{b_1} \simeq 1237.87 \text{ MeV}.$$

But: $f_\pi \simeq 4.07 \text{ MeV}.$

3 Options:

1) We made a mistake.

But: 2 out of 3 collaborators did the calculations independently (3^{rd} one is going around giving talks). Also recall that our results passed one non-trivial internal consistency check!

3 Options:

2) We have a good Lagrangian, but a bad wall.

Someone should do the soft wall! Or find a better wall.

3 Options:

3)

Summary:

Top-down models: successful models of strong coupling dynamics.

Bottom-up models: tuned to data, but not approximation to anything. Should be used with caution.