The Holographic Correspondence: A Useful Application of String Theory

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Main Message

Through the **holographic correspondence** (or **gauge/gravity**, or **AdS/CFT, gauge/string**, or **Maldacena correspondence** or **duality**), string theory provides a useful tool to study *some* aspects of *certain* **strongly-coupled field theories**

Why do we care?

- Results are useful to develop some intuition on strongly-coupled field theories remotely similar to QCD, BSM or condensed matter systems
- New theoretical paradigm: **equivalence** between GRAVITATIONAL and NON-GRAVITATIONAL theories!!
- Novel perspective on some difficult gravity problems
- Promotes contact between different physics communities

Disclaimers/Clarifications

- We are NOT claiming to have solved QCD, or something similar!! The field theories under present control, while interesting, are at best **toy models** of real-world QCD or CM
- This string theory **application** is orthogonal to the search for a unified theory. We're NOT looking for the Standard Model here

Then again, this IS string theory, arguably being **useful**

Plan

- Motivation: QCD and the QGP
- String Theory
- Holographic Correspondence
- Some Applications

My recent work in this area:

E. Cáceres, AG, hep-th/0606134 (JHEP)
M. Chernicoff, J.A. García, AG, hep-th/0607089 (JHEP)
M. Chernicoff, AG, hep-th/0611155 (JHEP)
M. Chernicoff, AG, 0803.3070 (JHEP)
M. Chernicoff, J.A. García, AG, 0903.2047 (PRL)
M. Chernicoff, J.A. García, AG, 0906.1592 (JHEP)
E.Cáceres, M.Chernicoff, AG, J.F.Pedraza, 1003.5332 (JHEP)
AG, J.F. Pedraza, 1102.4893 (JHEP)
M. Chernicoff, AG, J.F. Pedraza, 1106.4059 (JHEP)
C.A. Agón, AG, B.O. Larios, 1206.5005 (JHEP)

Quantum Chromodynamics:QCD

- Quarks $q_C^{(f)}(x)$ $C = 1,2,3$ $f = 1,\ldots,6$

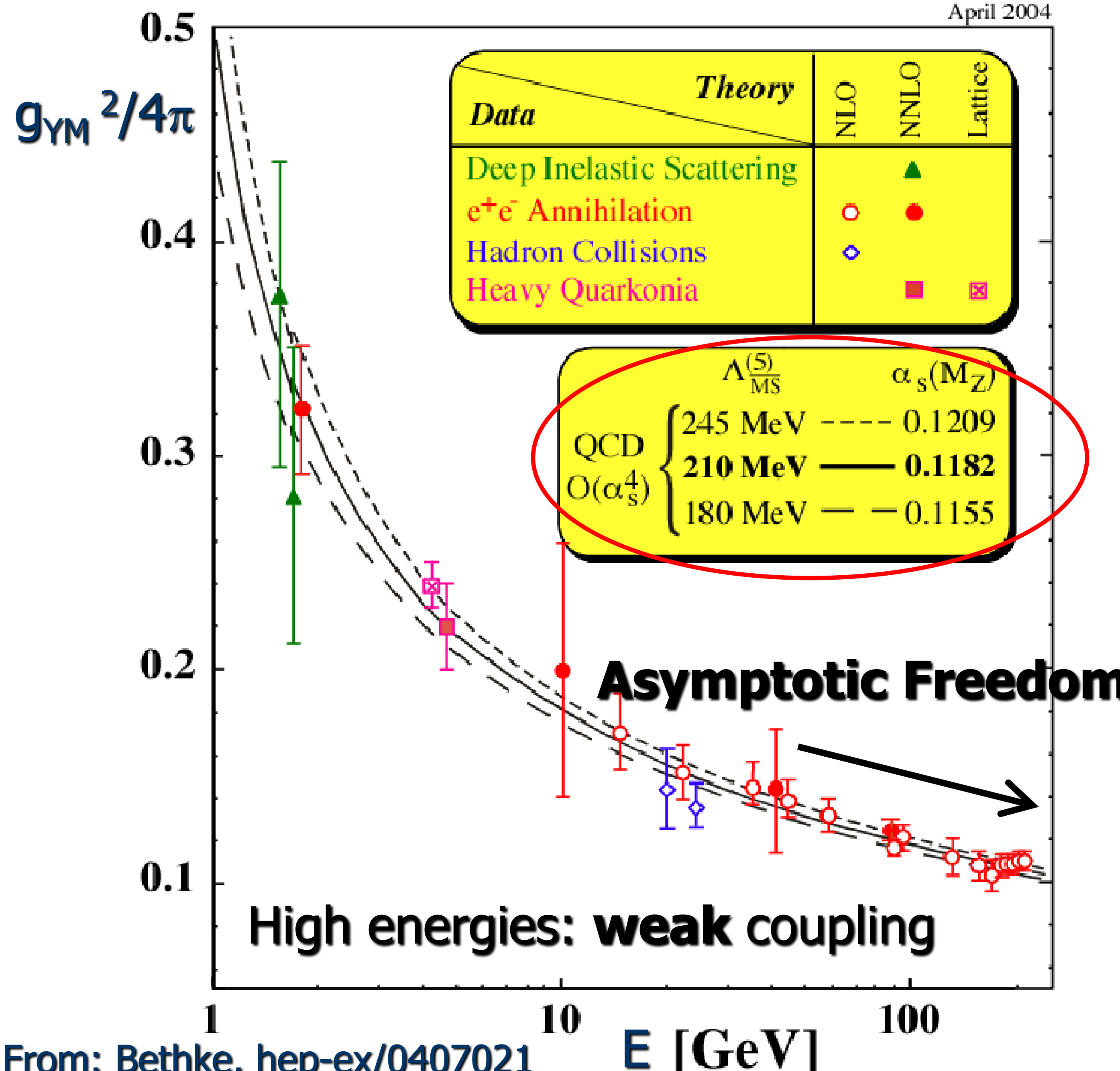
  \+ **3 colors** (*kinds* of strong charge) $SU(3)_c$

- Gluons $A^{\mu}_{CC'}(x) \equiv A^{\mu}_I(x) t^I_{CC'}$ $C, C' = 1,2,3$ $I = 1,\ldots,8$

$$S_{\mathrm{QCD}} = \int d^4x \left[\frac{1}{2g_{YM}^2} \mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) + \bar{q}^{(f)}(i\gamma^\mu D_\mu + m^{(f)}) q^{(f)} \right]$$

$$D_\mu \equiv \partial_\mu - i g_{\mathrm{YM}} A_\mu \qquad F_{\mu\nu} \equiv i\left[D_\mu, D_\nu \right]$$

coupling constant (*magnitude* of strong charge): controls interaction strength, and validity of perturbative expansion



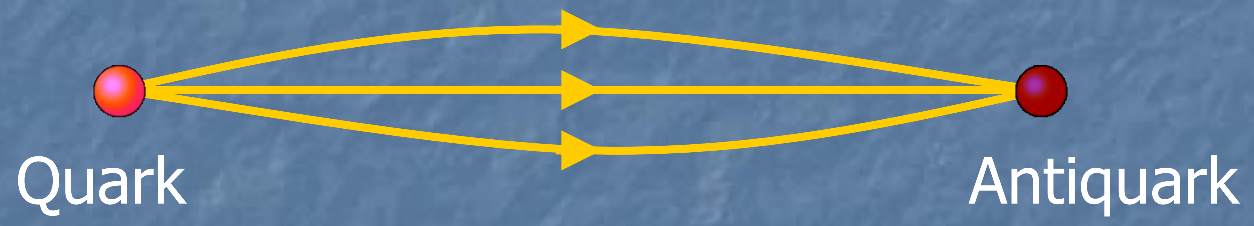
From: Bethke, hep-ex/0407021

QCD: Confinement

At low energies, coupling becomes so strong that we do NOT observe directly quarks and gluons, but **hadrons** (mesons, baryons, glueballs, etc.)

Only particles that are **color NEUTRAL**

Intuitively, reason is that color flux lines feel each other and therefore do not spread out:

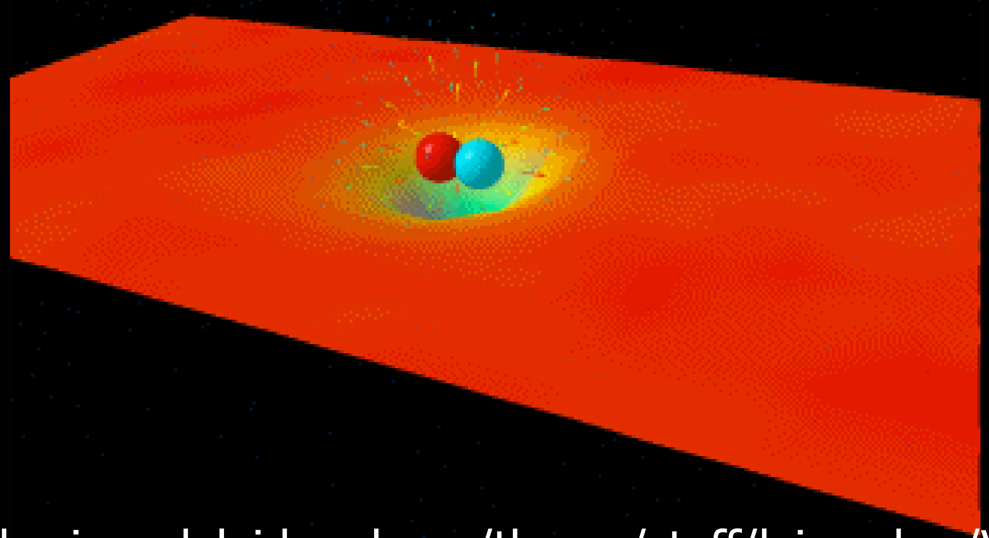


This '**flux tube**' gives rise to *linear* potential:

$$V_{q\bar{q}}(L) \simeq \sigma L$$

QCD: Confinement

Such ‘flux tubes’ are visible in numerical calculations on discretized spacetime– **lattice QCD**



http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/

Suggests connection between QCD and ‘fat’ strings (phenomenological model: `QCD string’ can reproduce “Regge behavior” $J = \alpha' m^2 + \alpha(0)$)

QCD: Deconfinement

Note that strong coupling is necessary (although not sufficient!) to have confinement

As we heat up a gas of hadrons, the coupling decreases…

We therefore expect phase transition to

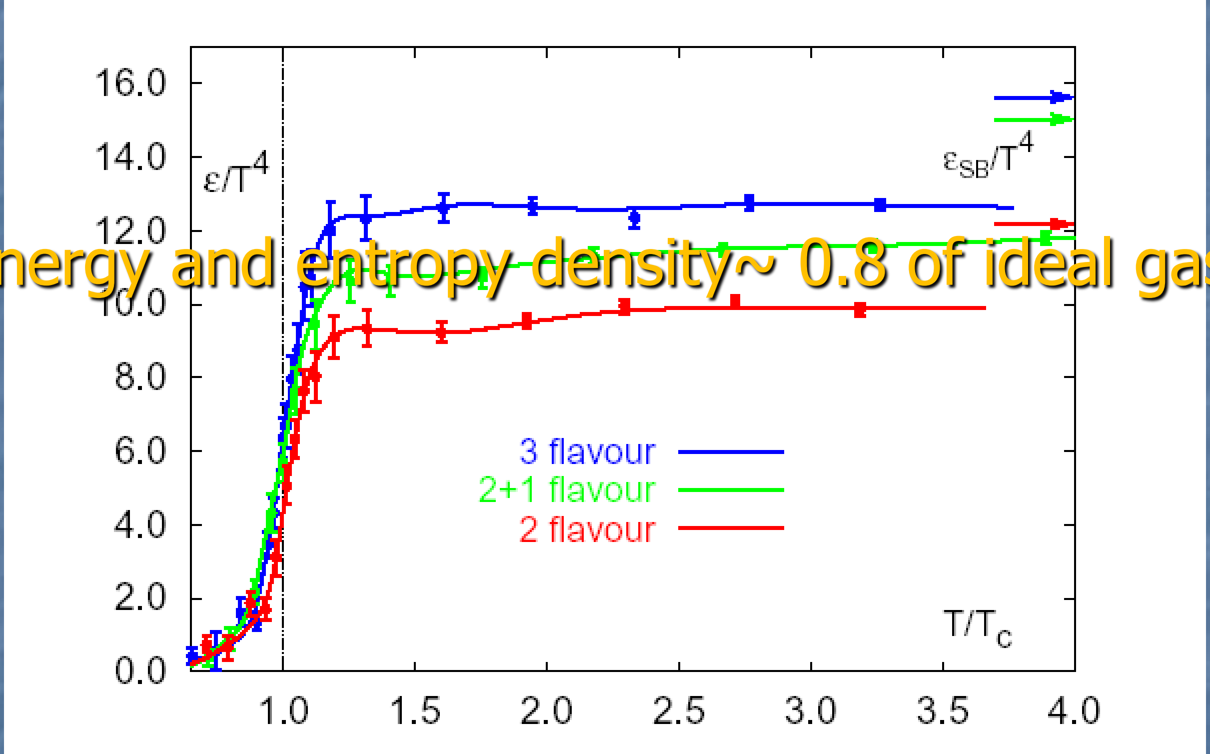
Quark-Gluon Plasma (QGP)

at a certain **deconfinement temperature**

$$T_c \approx \Lambda_{\mathrm{QCD}} \simeq 200\ \mathrm{MeV} \approx 2\times 10^{12}\,\mathrm{K}$$

QCD: Deconfinement

Lattice calculations confirm this, with $T_c \simeq 190\text{MeV}$



Energy and entropy density~ 0.8 of ideal gas

From: F. Karsch, hep-lat/0106019

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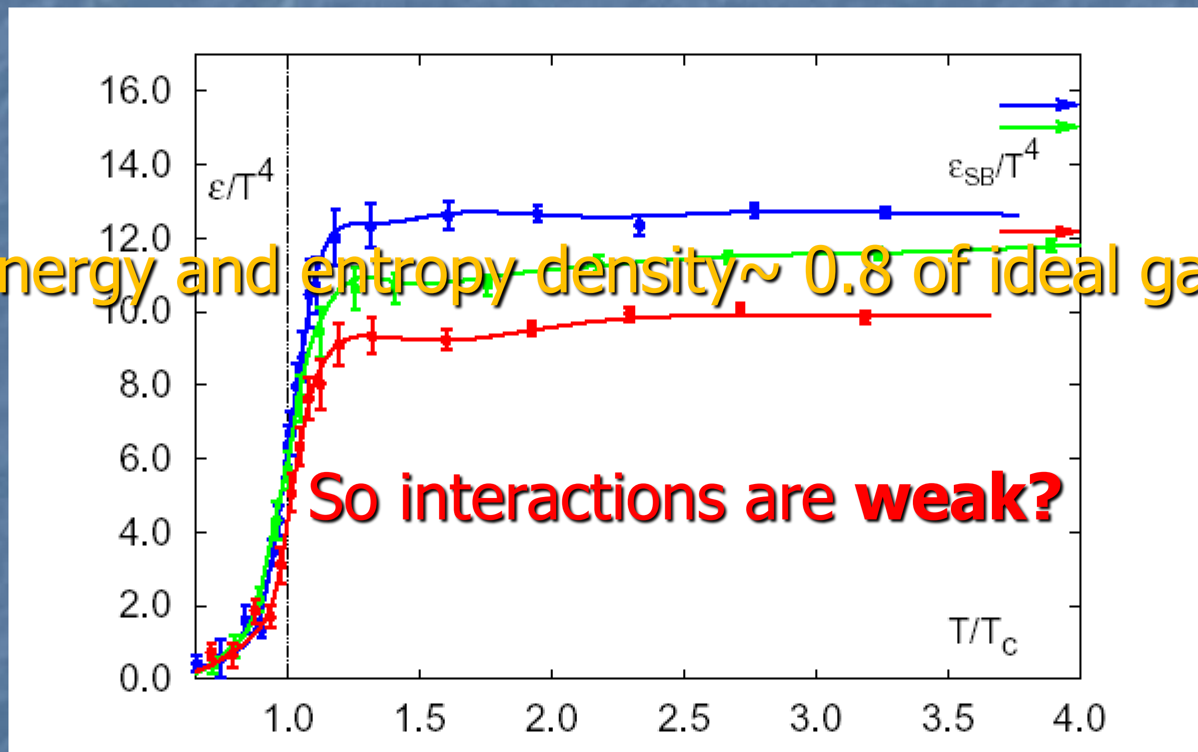


Energy and entropy density~ 0.8 of ideal gas

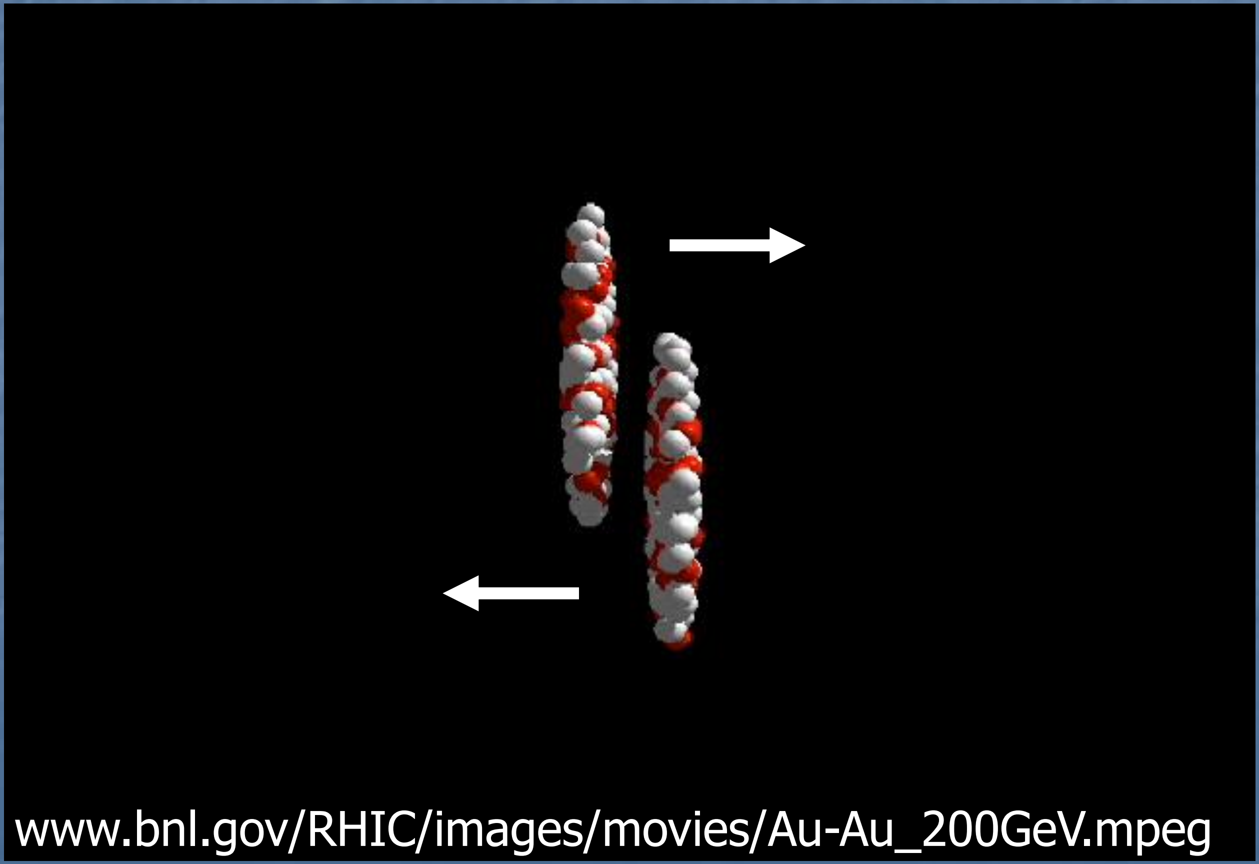
So interactions are **weak?**

From: F. Karsch, hep-lat/0106019

QGP at RHIC (and LHC)

Au+Au (400 nucleons)

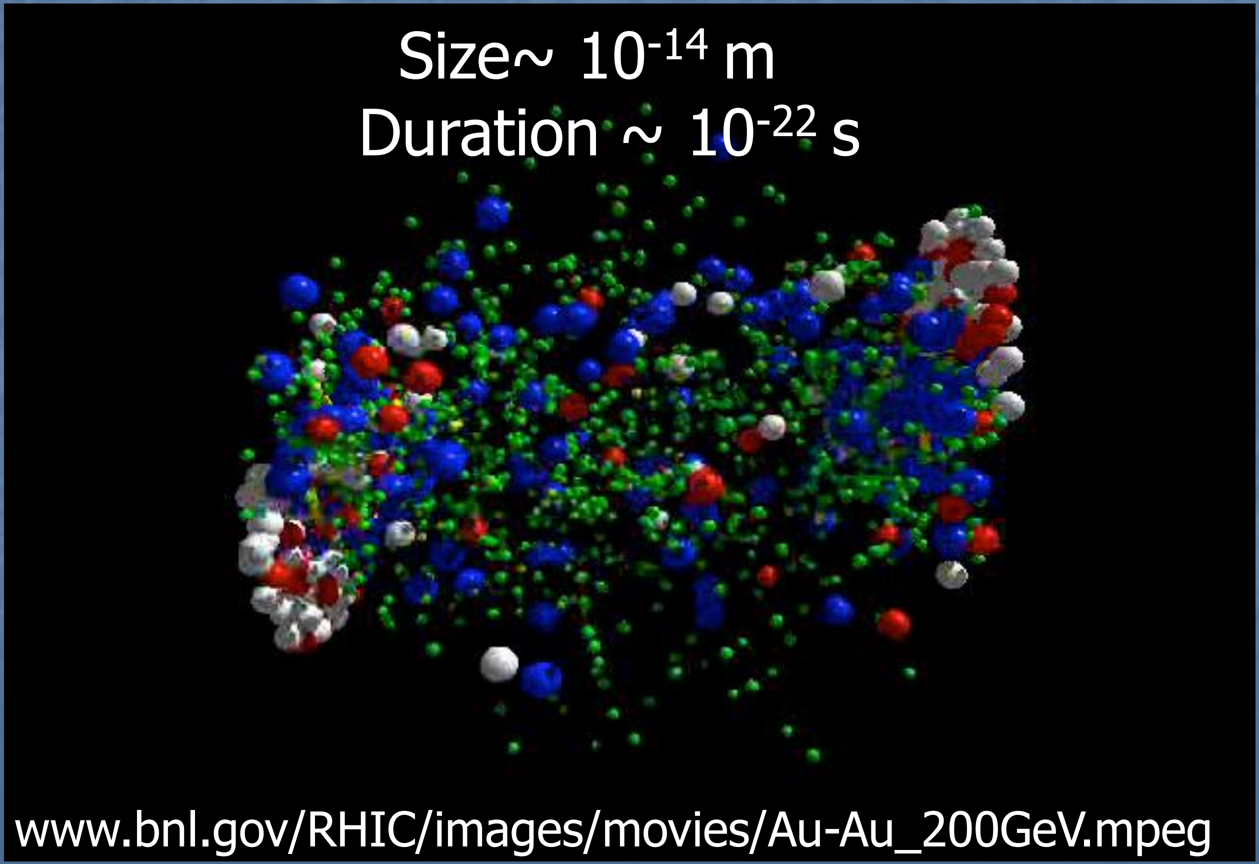
100 GeV/nucleon



QGP at RHIC (and LHC)

Au+Au (400 nucleons) → QGP → 5000 hadrons+etc.

100 GeV/nucleon ~2 GeV/hadron



QGP at RHIC (and LHC)

$\Rightarrow$ **Strongly-Coupled Plasma (sQGP)**

$$g_{YM}^2 \approx 3-10 \qquad g_{YM}^2 / 4\pi \approx 0.3-1$$

- **Perturbative** expansion unreliable
- (Euclidean) **Lattice** calculations useful to determine static properties, but NOT dynamical, or at finite density (chemical potential)…
- We can formulate **phenomenological models** …
- Or try to carry out first-principles calculations in a **different** (but hopefully similar) **theory:** a **solvable toy model** of QGP/QCD

A Distant Cousin of QCD

Yang-Mills (QCD w/o quarks): $A^{\mu}_{CC'}(x) \quad C, C' = 1, \ldots, N_c$

+ 6 massless real scalars: $\Phi^{I}_{CC'}(x) \quad I = 1, \ldots, 6$

+ 4 massless Weyl fermions: $\lambda^{A}_{\alpha CC'}(x) \quad A = 1, \ldots, 4$

+ carefully synchronized 3-pt and 4-pt interactions

$= SU(N_c)$ Super-Yang-Mills with $\mathcal{N} = 4$ supersymmetry

Theory invariant under **rescalings** even at the quantum level… g_{YM} does NOT run with energy!! [Sohnius,West]

This is a "**conformal field theory**"

Spacetime symmetry: $SO(4,2) \supset \text{Poincaré}(3,1) \supset SO(3,1)$

Conformal group ↑ (+ fermionic part)

(dilatations + special conformal transf. + Poincaré)

A Distant Cousin of QCD

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$= SU(N_c)$ Super-Yang-Mills with $\mathcal{N} = 4$ supersymmetry

Is this theory at least **qualitatively similar** to QCD??

QCD vs. $\mathcal{N} = 4$ SYM

- $T = 0$:

QCD		$\mathcal{N} = 4$ SYM
Asympt. free $dg_{YM}^2 / dE < 0$		Conformal $dg_{YM}^2 / dE = 0$
Confined in IR		Deconfined
Only massive particles	$\neq$	No mass scale
Linear Potential		Coulomb Potential
Non-Supersymmetric		Supersymmetric

- $T > T_c$:

QCD		$\mathcal{N} = 4$ SYM
Approx. conformal $\varepsilon \sim T^4$		Temp. is only scale $\varepsilon \propto T^4$
Deconfined		Deconfined
Plasma of gluons and quarks (QGP)	$\approx$	**Plasma of gluons and exotic matter (XGP)**
Screened Potential		Screened Potential
No Supersymmetry		Supersymmetry broken

The **holographic correspondence** relates this (and other) cousin(s) of QCD to **certain string theory(ies) living on a certain curved spacetime…**

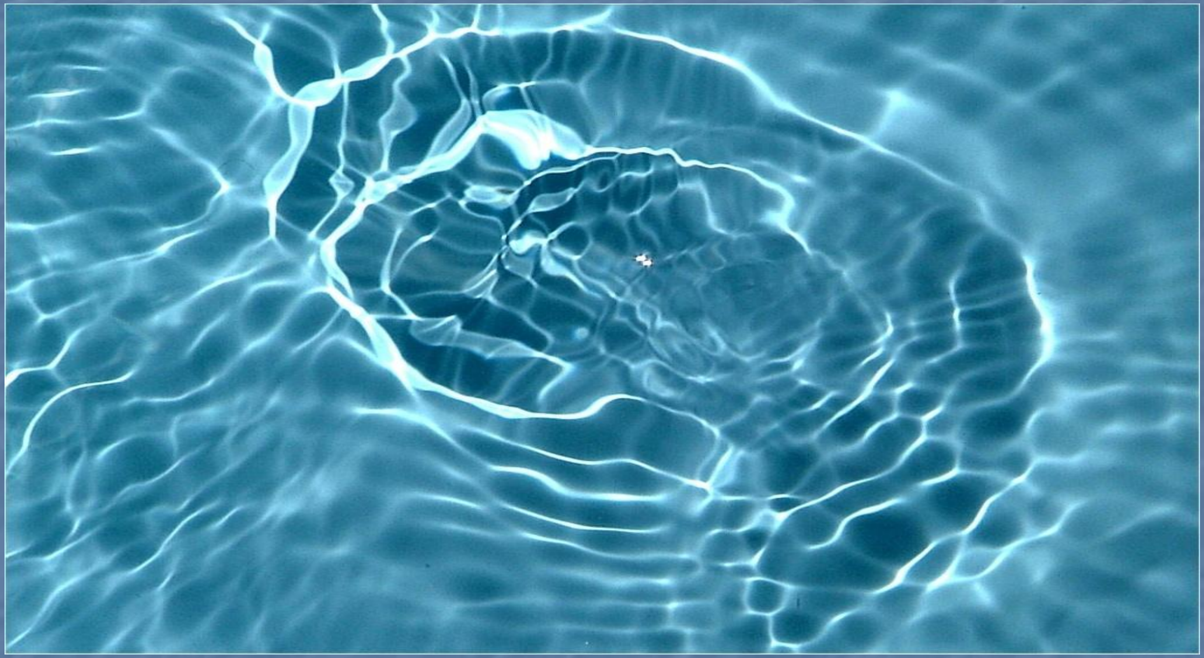
What is a String Theory?

Recall that a ‘particle’ physicist is really a “**field** physicist”:

Particles= small excitations of a quantum field

What is a String Theory?

Recall that a ‘particle’ physicist is really a “**field** physicist”:

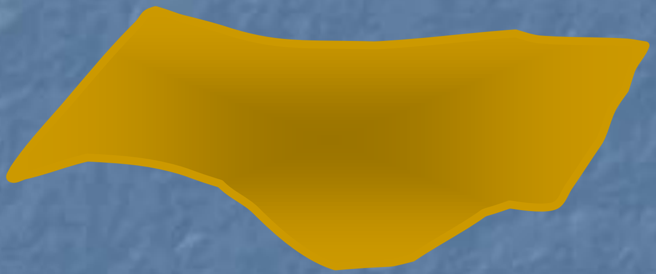


Soliton= large (finite energy) nonperturbative excitation of a quantum field

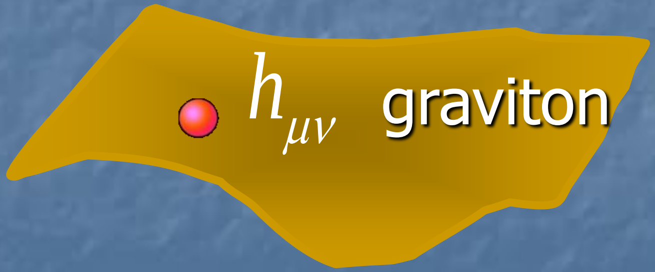
What is a String Theory?

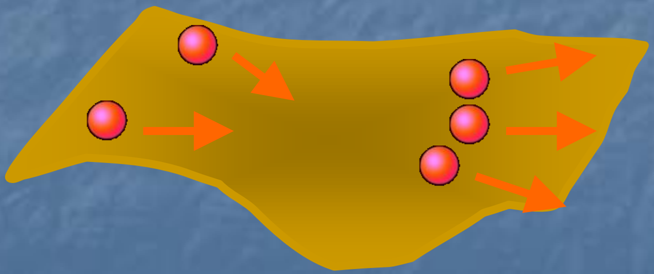
In particular, when confronted with

Gravity ↔ Spacetime ,



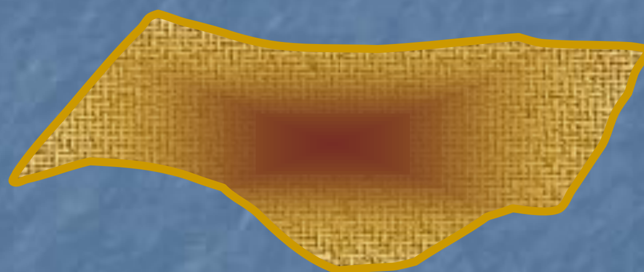
the particle/field physicist would start studying it as follows:





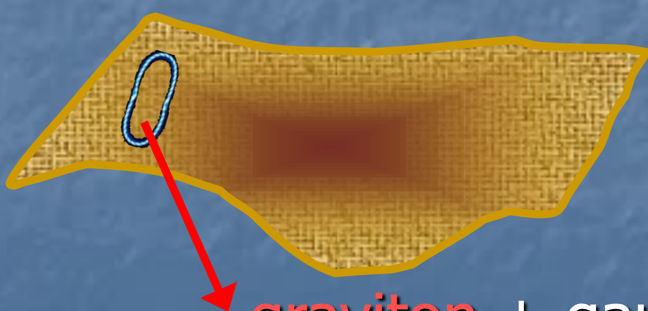
What is a String Theory?

Within **string theory**, spacetime is only part of a much more complex structure (~ a "string field")



whose small excitations are described by **strings**:

size l_s , coupling g_s



graviton + gauge bosons + fermions + etc.
(low energies: **Supergravity**)

What is a String Theory?

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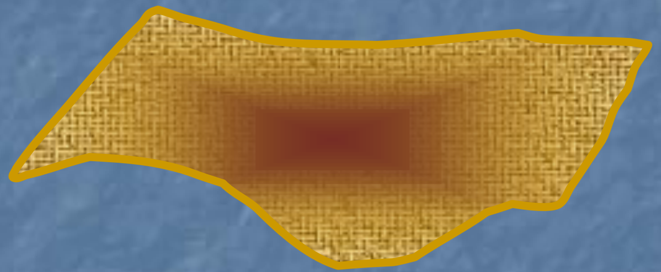
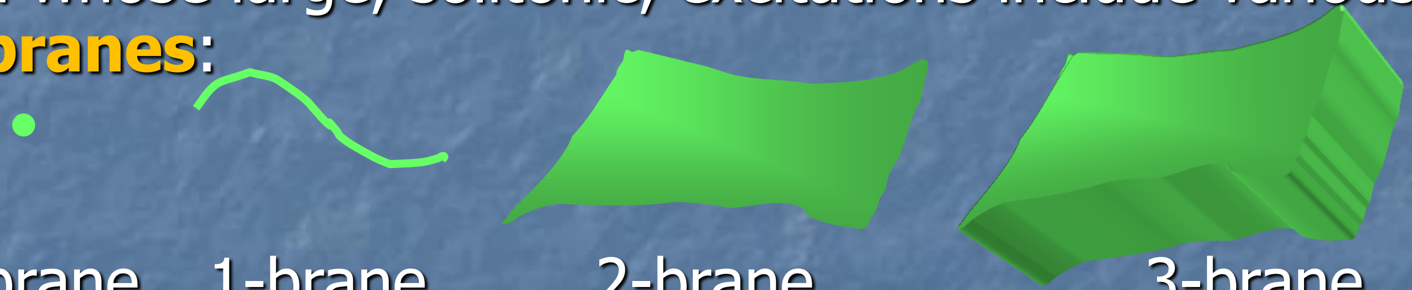


and whose large, solitonic, excitations include various **branes**:



0-brane 1-brane 2-brane 3-brane …

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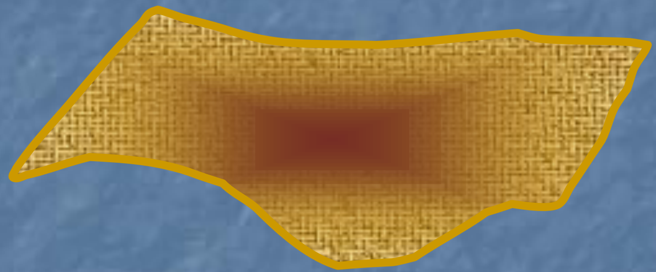


and whose large, solitonic, excitations include various **branes**:

…

with mass $m \propto 1/g_s$ (D-branes) or $m \propto 1/g_s{}^2$

non-Abelian gauge bosons + fermions + etc.

(low energies: **Super-Yang-Mills**)

A String Theory

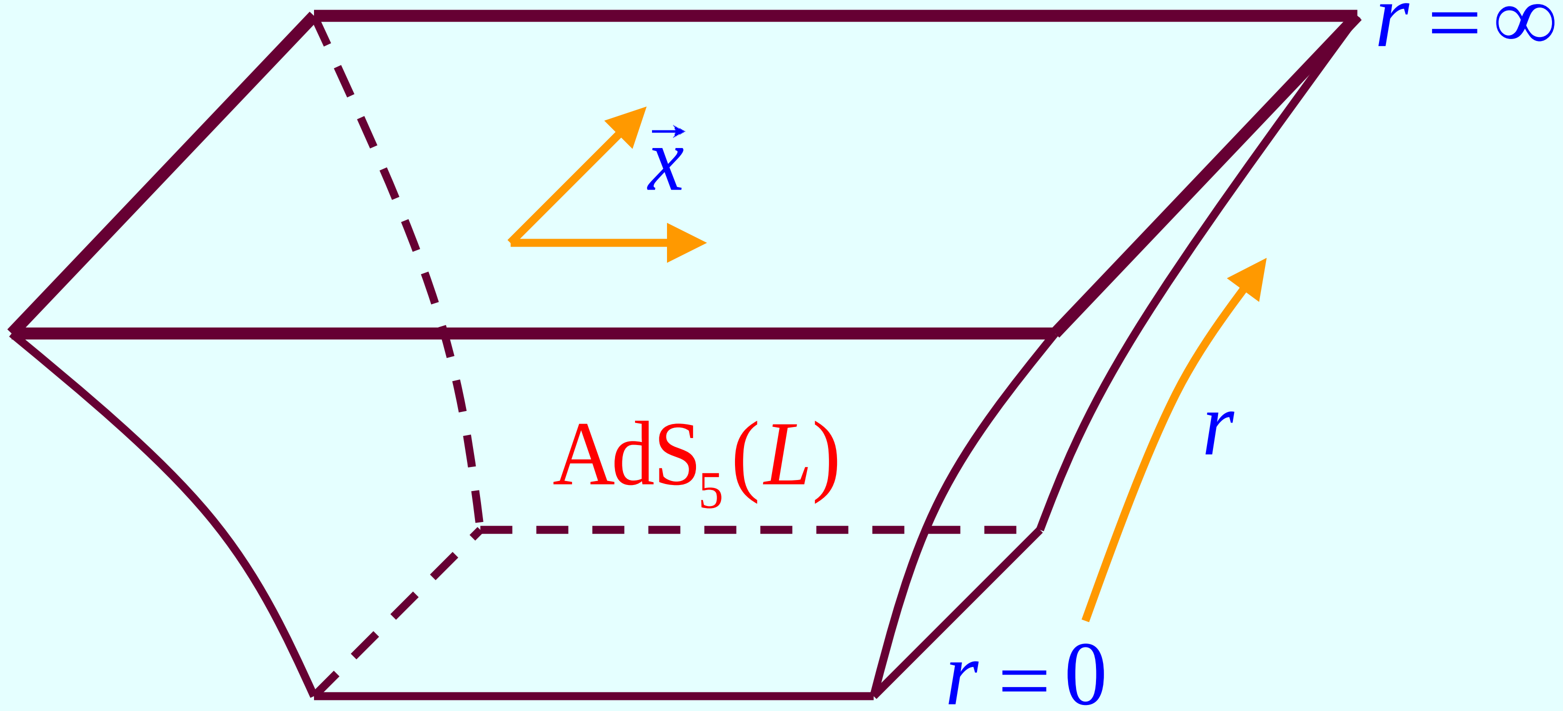
"IIB" Strings on $AdS_5 \times S^5$ (**anti-de Sitter** x sphere)

Spacetime with constant **negative** curvature (analog of a saddle)

A String Theory

"IIB" Strings on $AdS_5 \times S^5$ (**anti-de Sitter** x sphere)

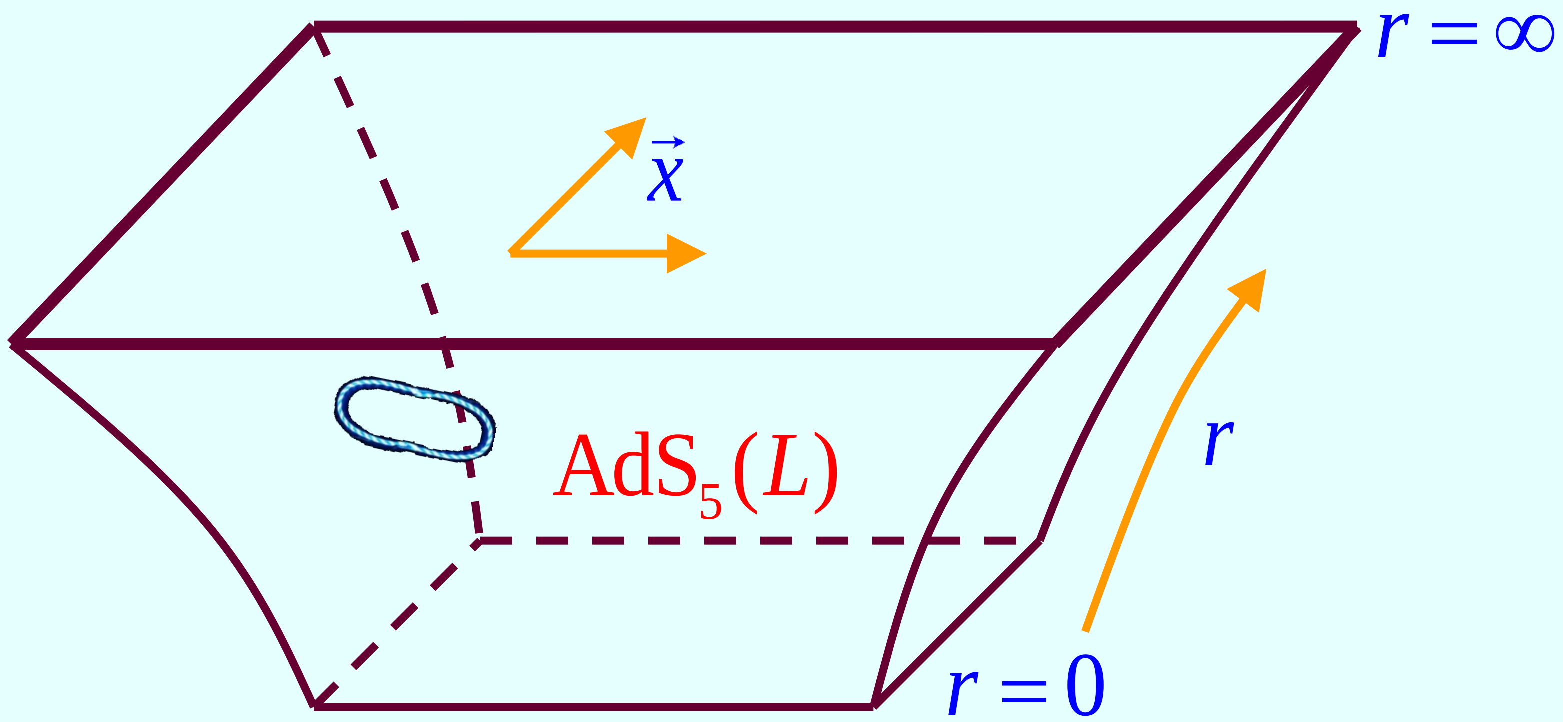
$$ds^2 = (r/L)^2(-dt^2 + d\vec{x}^2) + (L/r)^2 dr^2$$



A String Theory

Stringy fluctuations of this background can be small

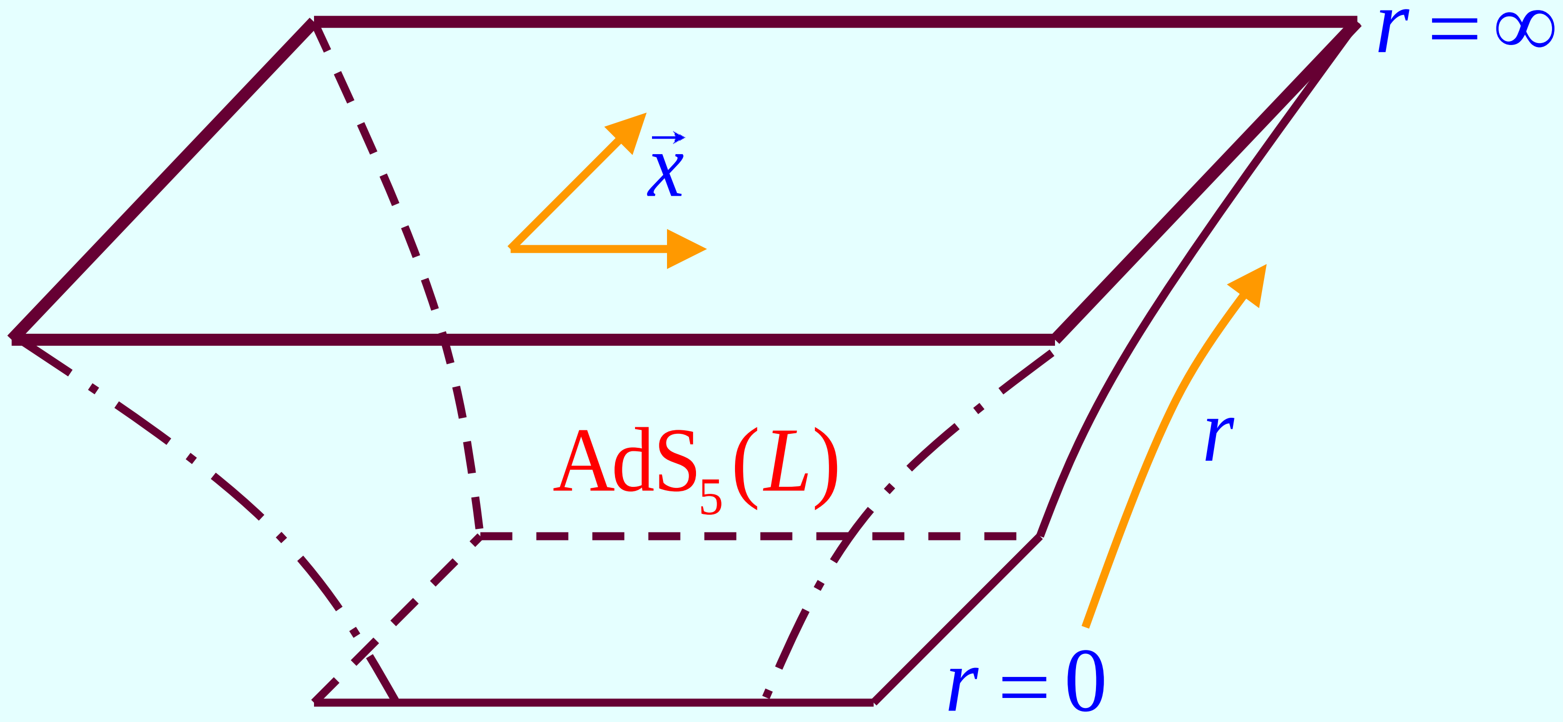
$$ds^2 = (r/L)^2(-dt^2 + d\vec{x}^2) + (L/r)^2 dr^2$$



A String Theory

Stringy fluctuations of this background can be small or large

$$ds^2 = (r/L)^2 g_{\mu\nu}(x,r)dx^\mu dx^\nu + (L/r)^2 dr^2$$



AdS/CFT Correspondence

$SU(N_c)$ $\mathcal{N}=4$ SYM on Mink. 3+1 [Maldacena] **=** IIB String Theory on **asymptotically** $AdS_5 \times S^5$

Particles	vs.	Strings
NO gravity		WITH gravity
WITH color		NO color
FLAT spacetime		CURVED dynamical spacetime
3+1 dim		9+1 dim

In spite of the marked differences, these 2 teories are **equivalent**: there is a dictionary that translates btwn. them

This equivalence sounds completely absurd, but 15 years and 8500 citations later, it still appears to be true!

AdS/CFT Correspondence

$SU(N_c)$ $\mathcal{N}=4$ SYM **=** IIB String Theory on
on Mink. 3+1 [Maldacena] **asymptotically** $AdS_5 \times S^5$

The mere **existence** of this connection is very surprising!!

Revolutionary idea: the presence/absence of **gravity**, y and the number of spacetime **dimensions**, can depend on our point of view!!

AdS/CFT Correspondence

$SU(N_c)$ $\mathcal{N}=4$ SYM **=** IIB String Theory on
on Mink. 3+1 [Maldacena] **asymptotically** $\mathrm{AdS}_5 \times \mathrm{S}^5$

NOTE: Neither of these 2 theories describes OUR universe!

They describe 2 **imaginary universes** (at best, crude toy models of ours), **which happen to be one and the same!!**

AdS/CFT Correspondence

$SU(N_c)$ $\mathcal{N}=4$ SYM **=** IIB String Theory on
on Mink. 3+1 [Maldacena] **asymptotically** $AdS_5 \times S^5$

Particles	vs.	Strings
NO gravity		WITH gravity
WITH color		NO color
FLAT spacetime		CURVED dynamical spacetime
3+1 dim		9+1 dim
STRONG coupling		WEAK coupling
WEAK		STRONG

So, besides absurd (and difficult to prove rigorously), this equivalence is **very useful**!!

AdS/CFT Correspondence

$SU(N_c)$ $\mathcal{N}=4$ SYM **=** IIB String Theory on
on Mink. 3+1 [Maldacena] **asymptotically** $AdS_5 \times S^5$

We can do string theory calculations only when the strings are **weakly coupled** and the spacetime is **not too strongly curved**

$$\Rightarrow g_{YM}^2 N_c \gg 1 \qquad N_c \gg 1$$

Perfect! For QGP we need $g_{YM}^2 N_c \approx 10-30$ $N_c = 3$

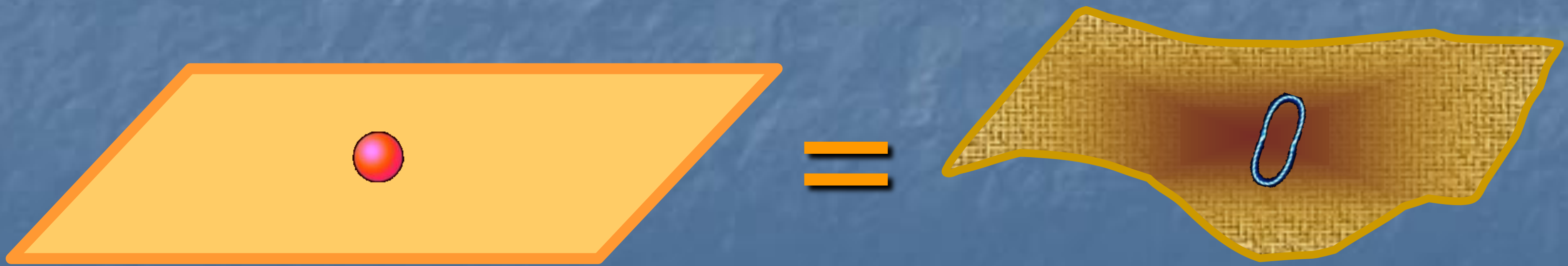
3>>1?? Lattice QCD: yes [Teper]

Gauge/Gravity Correspondence

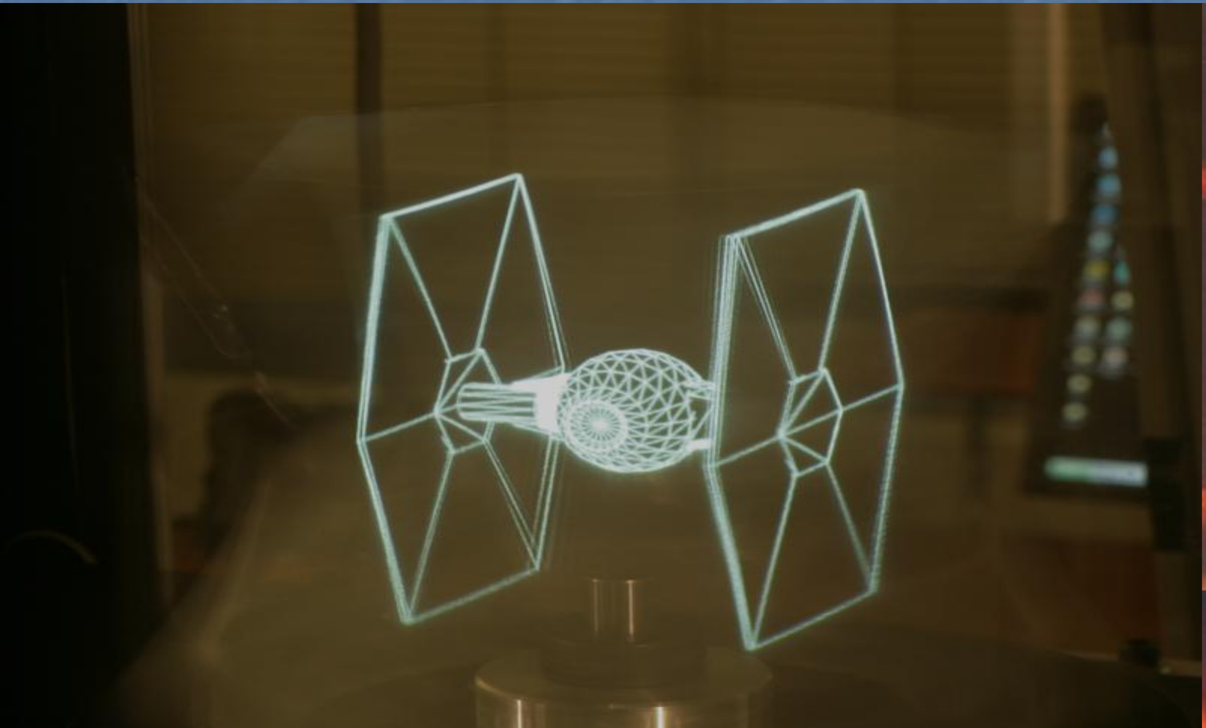
The preceding is just the best understood example of a more general **gauge/gravity correspondence**:

Quantum Field Theory in d dim = Gravity Theory in spacetime with D>d dim and certain asymptotics

This equivalence erases the dividing line between **field theories and string theories**!!



Holography



Just like a **hologram** is able to reproduce a 3D image from a 2D film, the field theory captures information about a gravity theory in **more dimensions**

Holographic Correspondence

- The preceding is just the best understood example of a more general **holographic correspondence**:

Quantum Field Theory in d dim = Gravity Theory in spacetime with D>d dim and certain asymptotics

- We know many other examples, e.g., involving closer cousins of QCD: with quarks, w/o supersymmetry, with confinement, with chiral symmetry breaking,…

[Sakai-Sugimoto(-Witten); Klebanov-Strassler; Maldacena-Núñez; Polchinski-Strassler; Freedman-Gubser-Pilch-Warner; etc.]

- But we do NOT know gravity dual of QCD, and the asymptotic freedom regime (weak coupling) would correspond to a highly curved spacetime region

AdS/CFT Correspondence

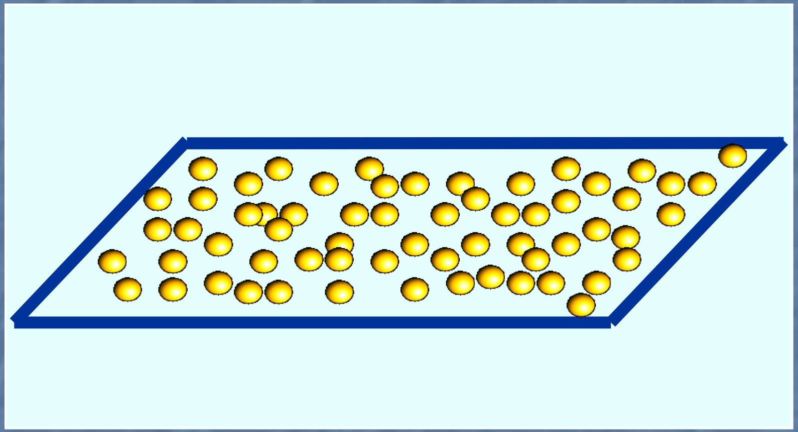
$SU(N_c)$ $\mathcal{N}=4$ SYM **=** IIB String Theory on
on Mink. 3+1 [Maldacena] **asymptotically** $AdS_5 \times S^5$

Geometry on right-hand side is **dynamical**:

SYM Vacuum	⟷	Pure $\mathbf{AdS_5}$ spacetime
Other SYM states	⟷	Excitations on $\mathbf{AdS_5}$
E.g., **thermal ensemble** in SYM	⟷	**Black hole** in $\mathbf{AdS_5}$!

AdS/CFT Correspondence

$$T \quad = \quad T_H \quad = \quad r_h / \pi L^2$$ [Hawking]



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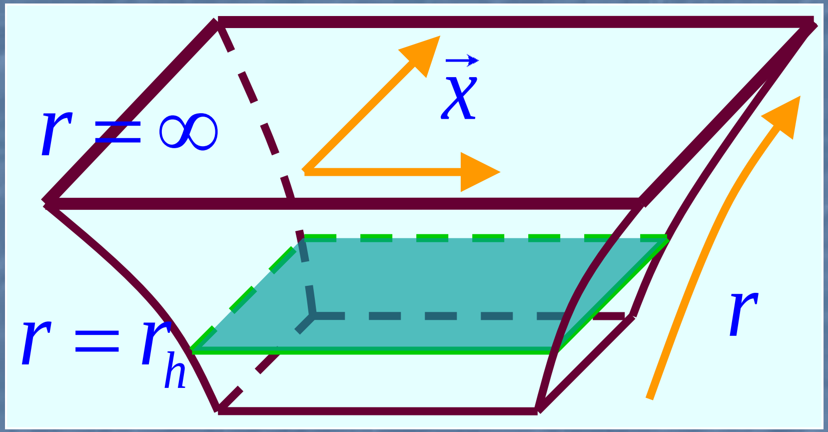
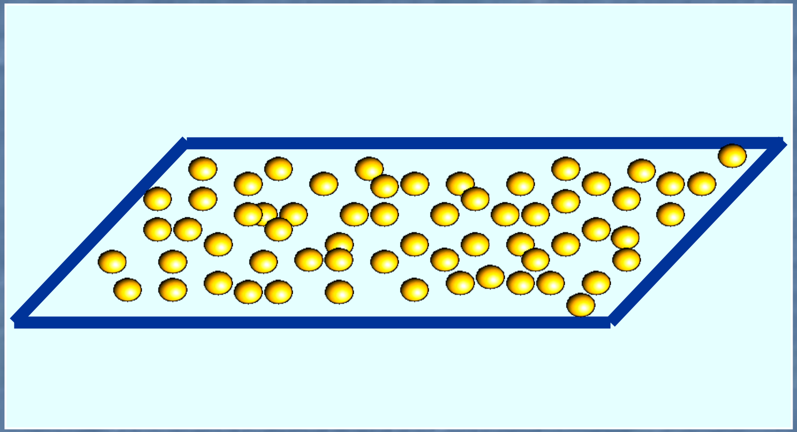


Plasma of gluons
(+ exotic matter)

Black hole in AdS!

$$ds^2 = \left(\frac{r}{L}\right)^2 \left(-\left(1-\tfrac{r_h^4}{r^4}\right)dt^2 + d\vec{x}^2\right) + \frac{L^2 dr^2}{r^2\left(1-\tfrac{r_h^4}{r^4}\right)}$$

Application 1: Entropy



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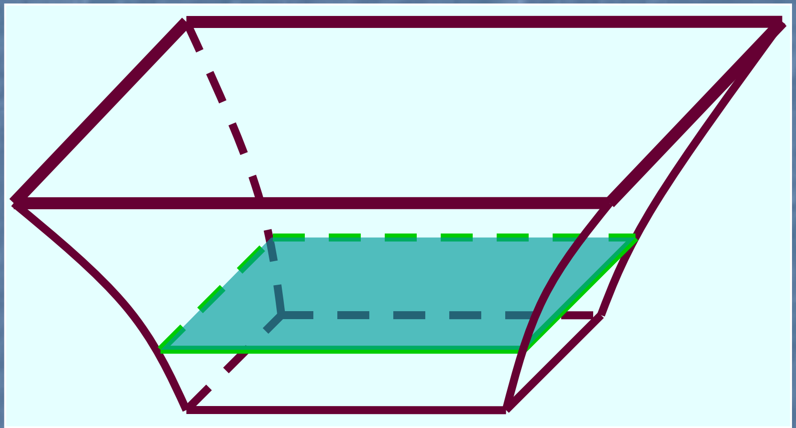
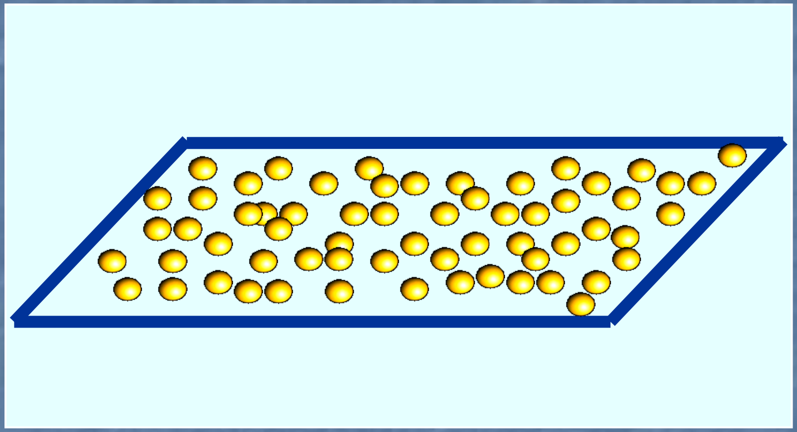


$$S_{\text{plasma}} = S_{\text{BH}} = \frac{A_H}{4G_N}$$

[Bekenstein,Hawking]

Application 1: Entropy



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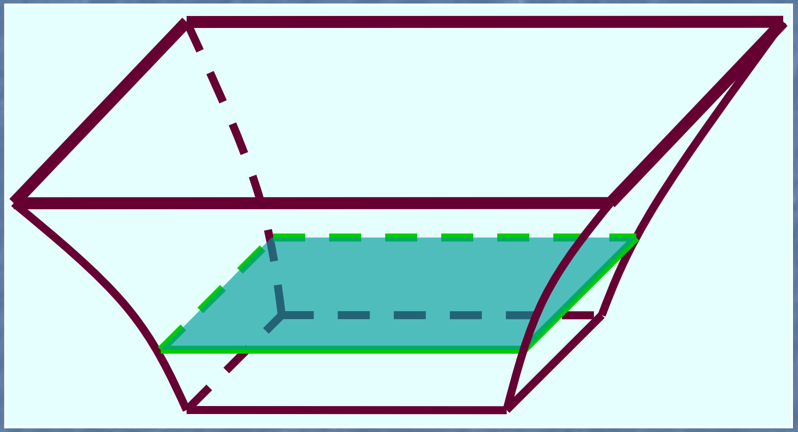


$$g_{YM}^2 N_c \ll 1 \quad \Rightarrow$$

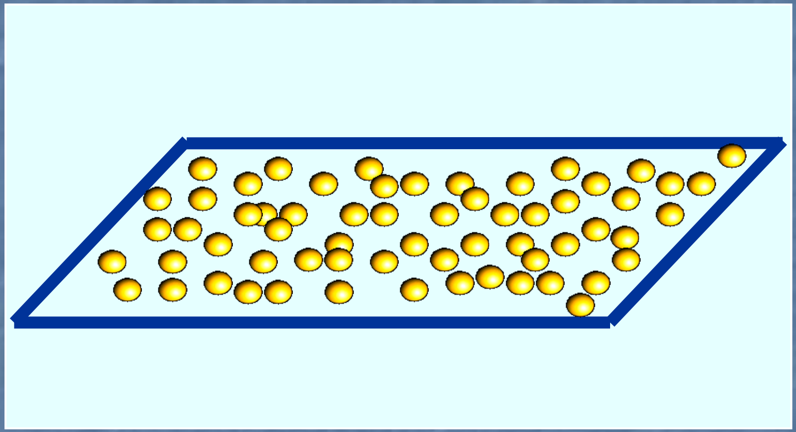
$$S_{\text{plasma}} = \frac{2\pi^2}{3} N_c^2 T^3 V$$

$$g_{YM}^2 N_c \gg 1 \quad \Rightarrow$$

$$S_{\text{BH}} = \frac{2\pi^2}{3} N_c^2 T^3 V \left(\frac{3}{4}\right)$$

[Gubser,Klebanov,Peet]

Application 1: Entropy



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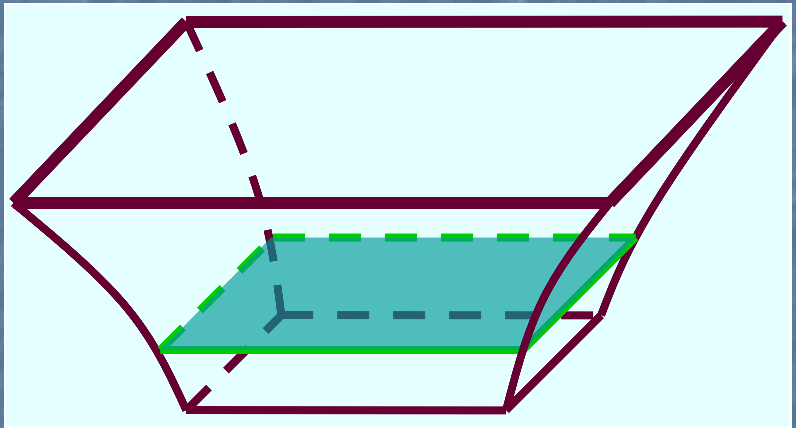


$$g_{YM}^2 N_c \ll 1 \quad \Rightarrow$$

$$S_{\text{plasma}} = \frac{2\pi^2}{3} N_c^2 T^3 V \left(1 - \frac{3 g_{YM}^2 N_c}{4\pi^2} + \cdots \right)$$

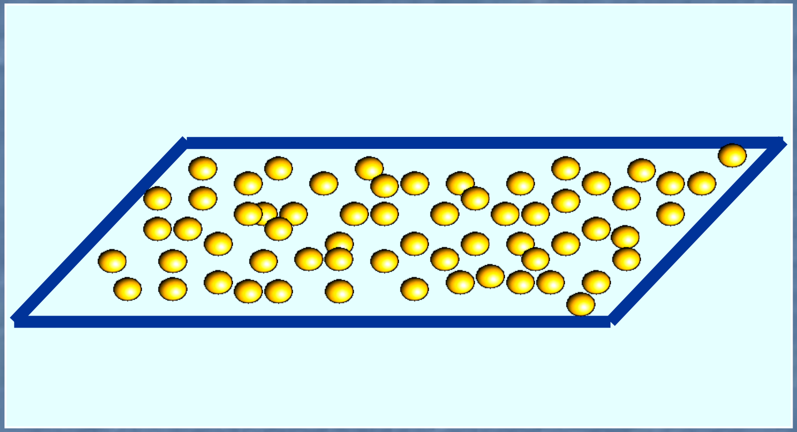
[Gubser,Klebanov,Peet;
Fotopoulos,Taylor]

$$g_{YM}^2 N_c \gg 1 \quad \Rightarrow$$

$$S_{\text{BH}} = \frac{2\pi^2}{3} N_c^2 T^3 V \left(\frac{3}{4} + \frac{45\zeta(3)}{64\sqrt{2}\left(g_{YM}^2 N_c\right)^{3/2}} + \cdots \right)$$

[Gubser,Klebanov,Peet;
Gubser,Klebanov,Tseytlin]

Application 1: Entropy



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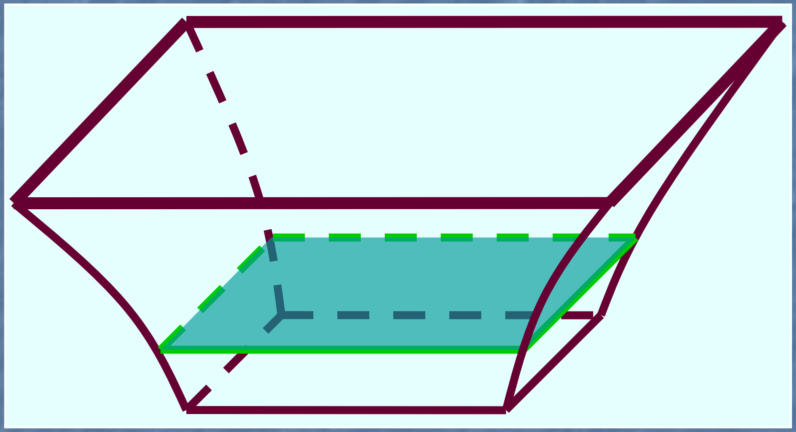


$$g_{YM}^2 N_c \ll 1 \quad \Rightarrow$$

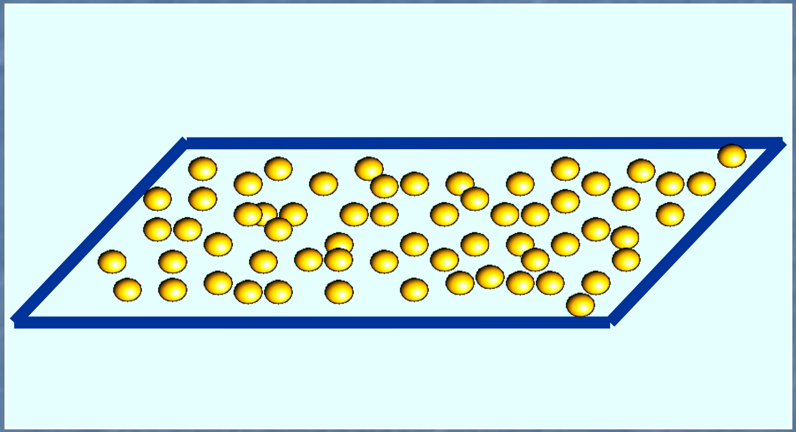
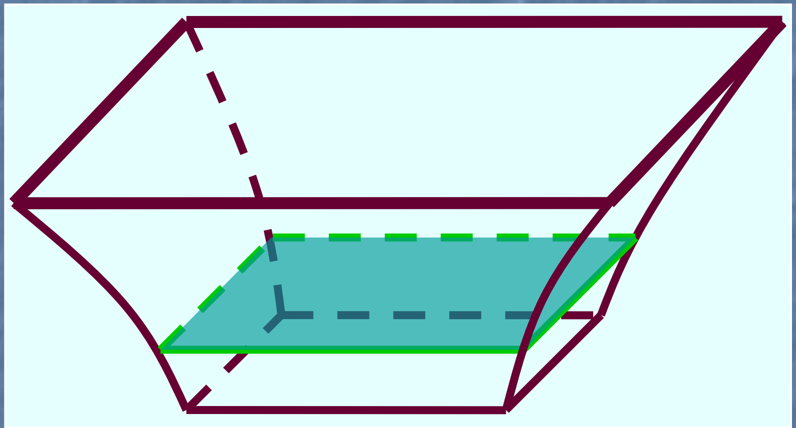
$$S_{\text{plasma}} = \frac{2\pi^2}{3} N_c^2 T^3 V \left(1 - \frac{3 g_{YM}^2 N_c}{4\pi^2} + \cdots \right)$$

$$g_{YM}^2 N_c \gg 1 \quad \Rightarrow$$

$$S_{\text{BH}} = \frac{2\pi^2}{3} N_c^2 T^3 V \left(\frac{3}{4} + \frac{45\zeta(3)}{64\sqrt{2}\left(g_{YM}^2 N_c\right)^{3/2}} + \cdots \right)$$

This is a **first-principles** result in **strongly-coupled** $\mathcal{N} = \mathbf{4}$ SYM (interesting in itself)…

Application 1: Entropy

 = 

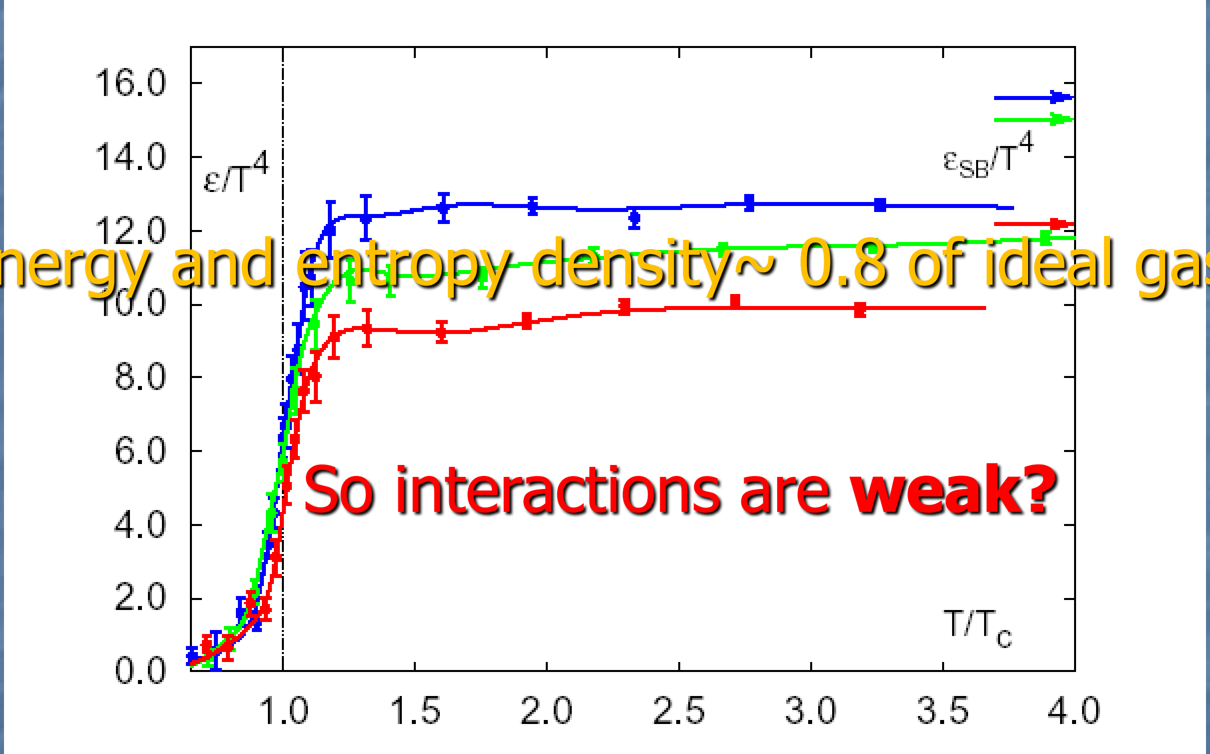
$$g_{YM}^2 N_c \ll 1 \quad \Rightarrow \qquad\qquad g_{YM}^2 N_c \gg 1 \quad \Rightarrow$$

$$S_{\text{plasma}} = \frac{2\pi^2}{3} N_c^2 T^3 V \left(1 - \frac{3 g_{YM}^2 N_c}{4\pi^2} + \cdots \right) \qquad S_{\text{BH}} = \frac{2\pi^2}{3} N_c^2 T^3 V \left(\frac{3}{4} + \frac{45\zeta(3)}{64\sqrt{2}\left(g_{YM}^2 N_c\right)^{3/2}} + \cdots \right)$$

… which can also be regarded as a **crude toy model** for entropy in QCD (available from lattice)…

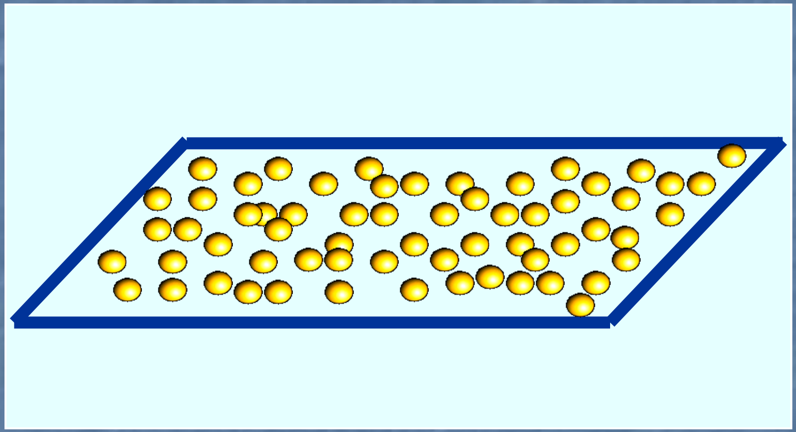
QCD: Deconfinement

Lattice calculations confirm this, with $T_c \simeq 190\mathrm{MeV}$



From: F. Karsch, hep-lat/0106019

Application 1: Entropy



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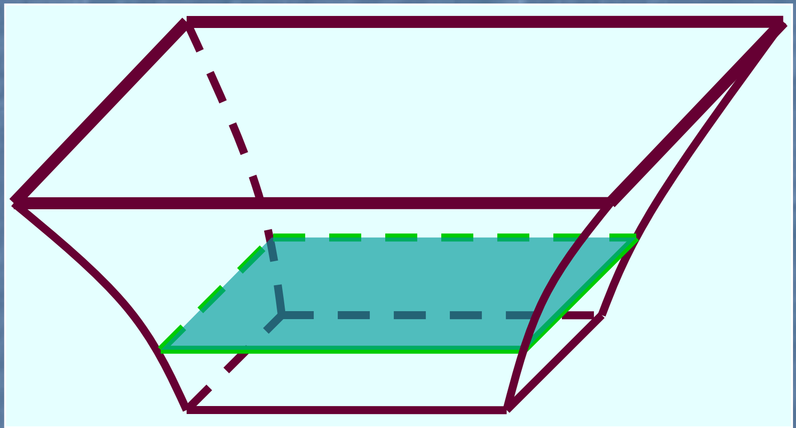

$$g_{YM}^2 N_c \ll 1 \quad \Rightarrow$$

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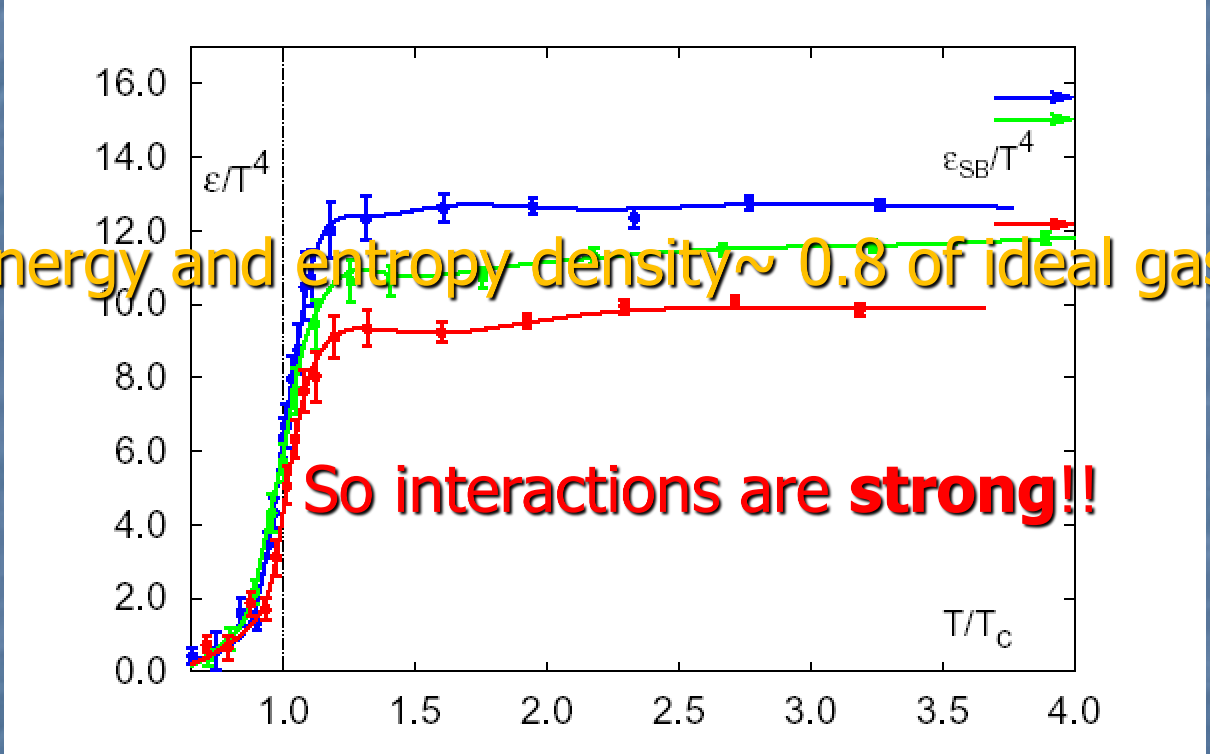
[Gubser,Klebanov,Peet]

$$\frac{S(g_{YM}^2 N_c = \infty)}{S(g_{YM}^2 N_c = 0)} = 0.75$$ close to ~ 0.8 of lattice QCD!

QCD: Deconfinement

Lattice calculations confirm this, with $T_c \simeq 190\text{MeV}$

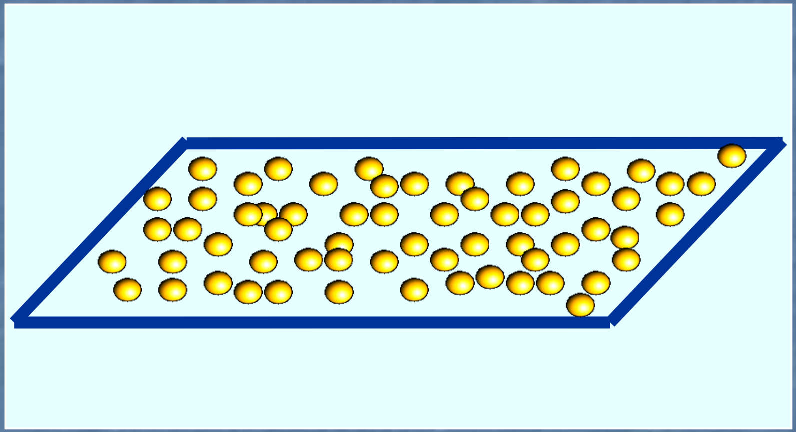


Energy and entropy density~ 0.8 of ideal gas

So interactions are **strong**!!

From: F. Karsch, hep-lat/0106019

Application 2: (Shear) Viscosity



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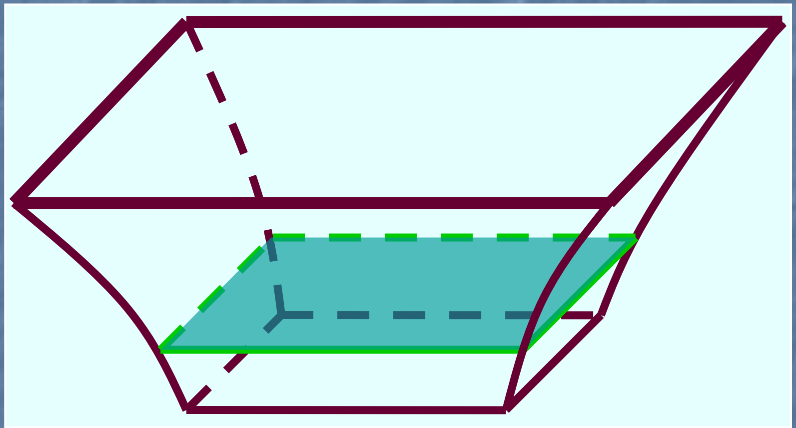


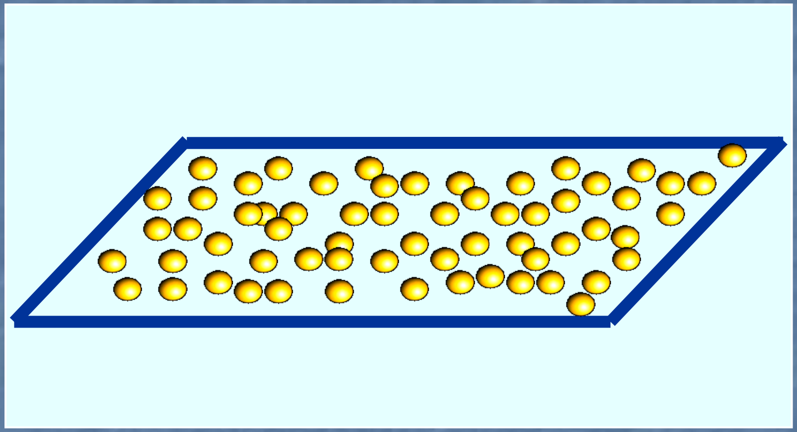
$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int d^4x\, e^{i\omega t} \left\langle \left[T_{xy}(x), T_{xy}(0) \right] \right\rangle \quad = \quad \lim_{\omega \to 0} \frac{1}{16\pi G_N} \sigma_{h_{\mu\nu}}(\omega)$$

[Kubo]

[Callan; Gubser, Klebanov, Polyakov; Witten]

- 2-point correlation function of energy-momentum tensor
- Absorption cross section for gravitons

Application 2: (Shear) Viscosity



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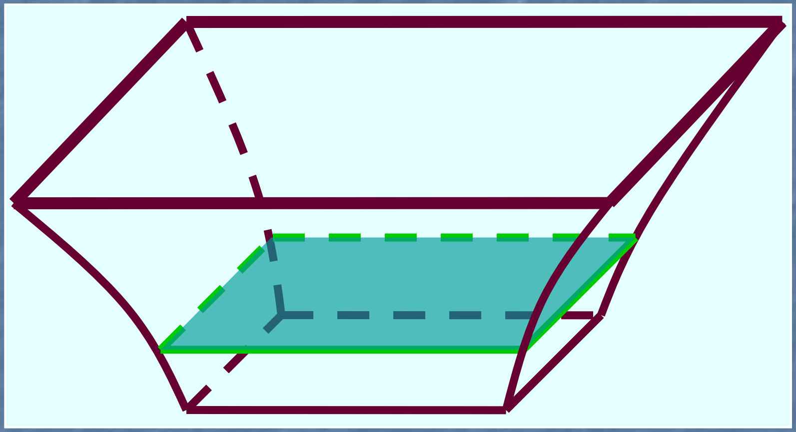

$$g_{YM}^2 N \ll 1 \quad \Rightarrow$$

$$\frac{\eta}{s} \sim \frac{\hbar / k_B}{(g_{YM}^2 N)^2 \log(1/g_{YM}^2 N)} \gg \frac{\hbar}{k_B}$$

[Arnold,Moore,Yaffe]

$$g_{YM}^2 N \gg 1 \quad \Rightarrow$$

$$\frac{\eta}{s} = \frac{\hbar}{k_B}\left(\frac{1}{4\pi} + \frac{135\zeta(3)}{64\sqrt{2}\pi(g_{YM}^2 N)^{3/2}} + \ldots\right) \ll \frac{\hbar}{k_B}$$

[Policastro,Son,Starinets;Buchel,Liu,Starinets]

Close to value ~0.1-0.2 estimated at RHIC and LHC!!

And **universal**: same value in all gauge/gravity examples!

Application 2: (Shear) Viscosity

Curious fact:

Viscosity of **pitch** (=brea)
~ 10^{11} larger than **water**

Viscosity of **QGP**
~ 10^3 larger than **pitch**!

But QGP's viscosity/entropy takes **lowest known** value in Nature

$$\frac{\eta}{s} \sim \frac{\hbar}{k_B}\frac{1}{4\pi}$$

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by Brookhaven Science Associates, a company
founded by Stony Brook University and Battelle

News Release

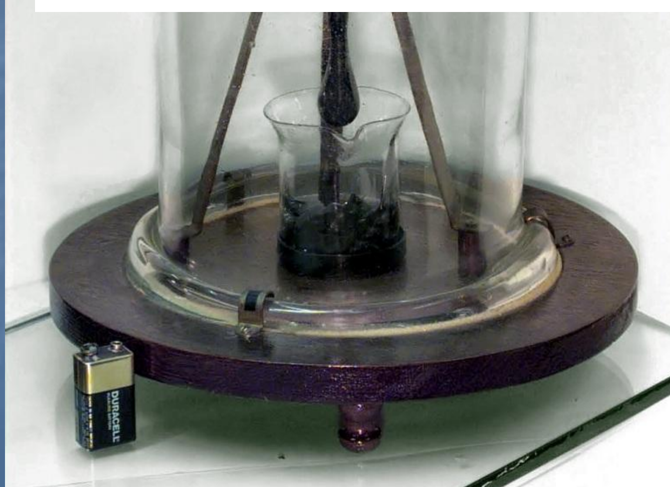
Number: 05-38

For release on April 18, 2005, 9:00:00 AM

Contacts: Karen McNulty Walsh, (631) 344-8350 or Peter Genzer, (631) 344-3174

RHIC Scientists Serve Up "Perfect" Liquid

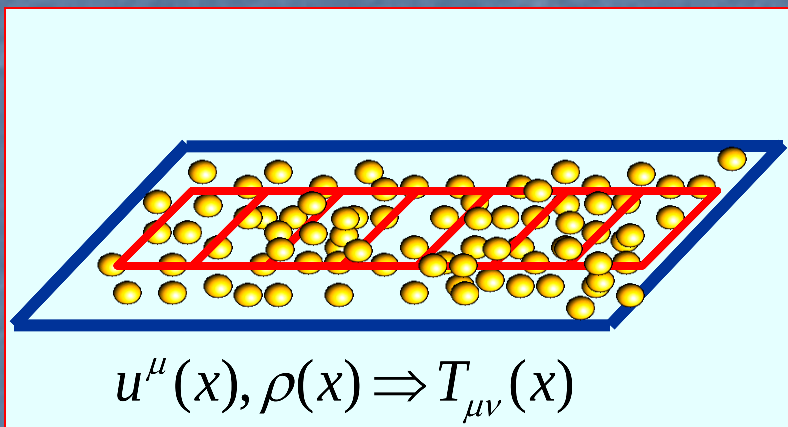
New state of matter more remarkable than predicted -- raising many new questions



But QGP's viscosity/entropy takes **lowest known** value in Nature

$$\frac{\eta}{s} \sim \frac{\hbar}{k_B} \frac{1}{4\pi}$$

Application 3: Fluids/Gravity



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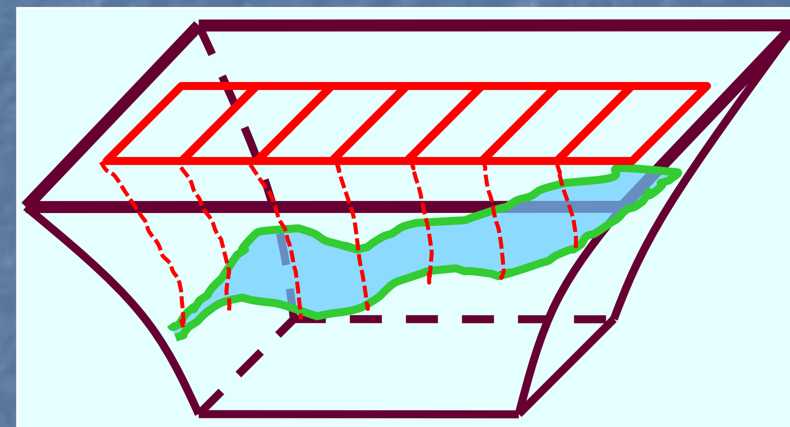


Hydrodynamical description

$$\partial_{\mu} T^{\mu\nu} = 0$$
$$(\mu, \nu = 0, \ldots, 3)$$

↔

Nonuniform black hole

$$R_{mn} - \tfrac{1}{2} R g_{mn} = -\Lambda g_{mn}$$
$$(m, n = 0, \ldots, 3, r)$$

[Bhattacharyya,Hubeny,Minwalla,Rangamani]

Navier-Stokes = Einstein!!

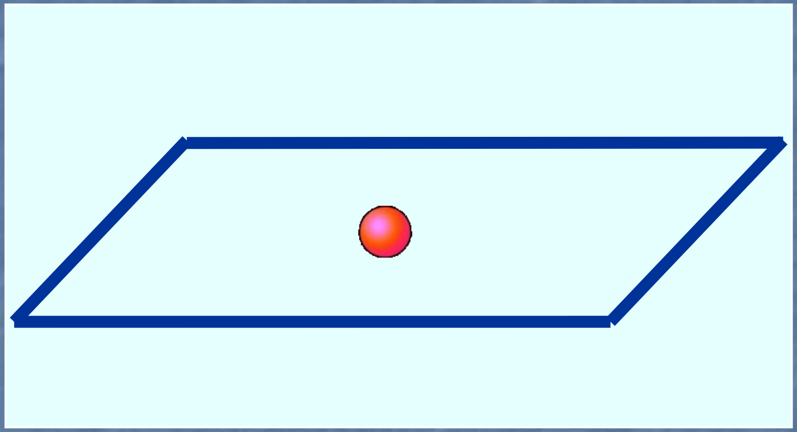
- Results have been obtained for **2nd order hydrodynamics** (in derivative expansion), determining terms that are needed for numerical simulations

  [Baier,Romatschke,Son,Starinets,Stephanov; Bhattacharyya,Hubeny,Minwalla,Rangamani; etc.]

- Besides shear viscosity, **other transport coefficients** have been obtained via holographic calculations: bulk viscosity, charge diffusion constant, electric conductivity, thermal conductivity, chiral magnetic effect, chiral vortical effect, etc.

  [Policastro,Son,Starinets;Buchel,Liu,Starinets; Buchel; Parnachev,Starinets; Kovtun,Starinets; Benincasa,Buchel,Starinets; Janik,Peschanski; Mas; Son,Starinets; Saremi; Buchel; Maeda,Natsuume,Okamura; Benincasa,Buchel; Benincasa,Buchel,Naryshkin; Janik; Mateos,Myers,Thomson; Liao,Shuryak; Bak,Janik; Erdmenger,Haack,Kaminski,Yarom; Banerjee,Bhattacharyya,Bhattacharyya,Dutta,Loganayagam,Surowka; Son,Surowka; Khaarzev,Son; etc.]

Quarks



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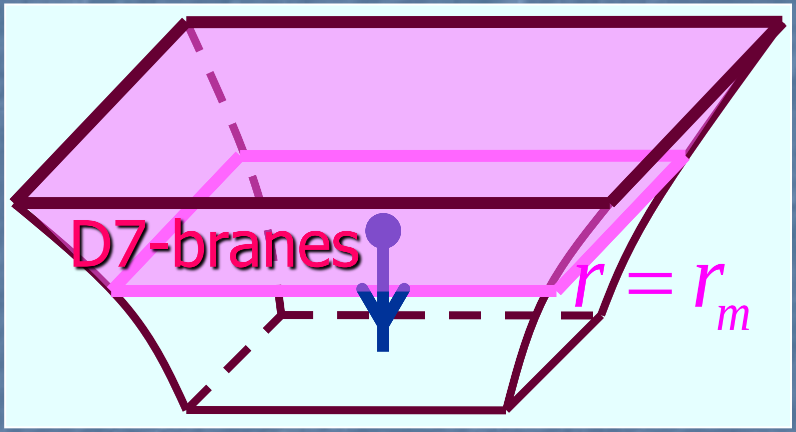


Quark with mass $m \leq \infty$ = String w/endpoint at $r_m \leq \infty$

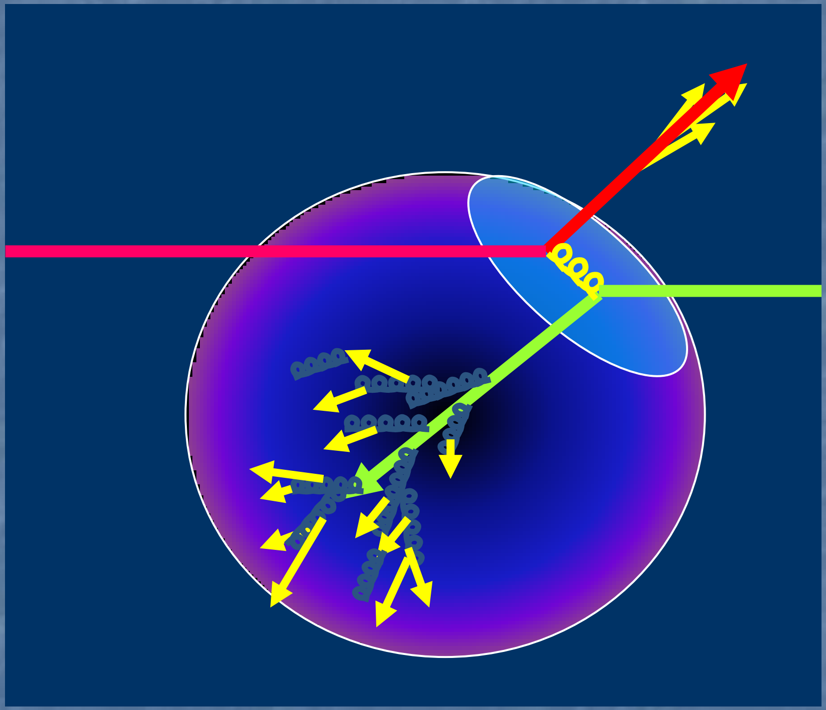
[Karch, Katz]

$$\frac{m}{\sqrt{g_{YM}^2 N_c}} = \frac{r_m}{2\pi L^2}$$

(Back to flux-tube=QCD string connection, except here string is infinitesimally thin!)

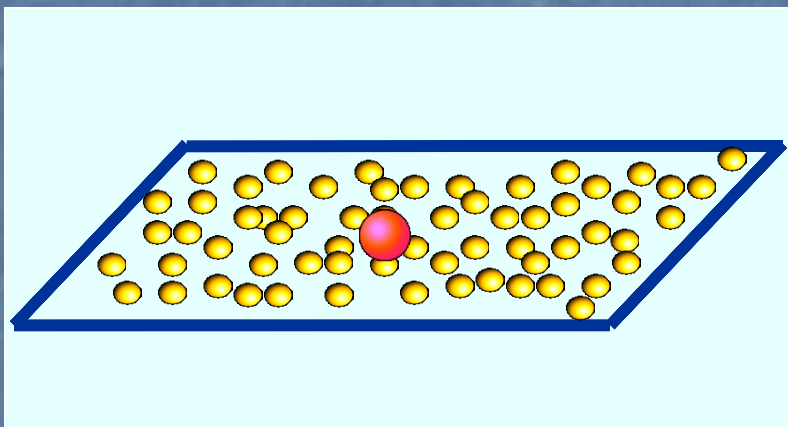
Application 4: Energy Loss

RHIC/LHC finds **significant energy loss** of quarks traversing the plasma ("jet quenching")



How much energy is lost?
Where does this energy go?

Application 4: Energy Loss



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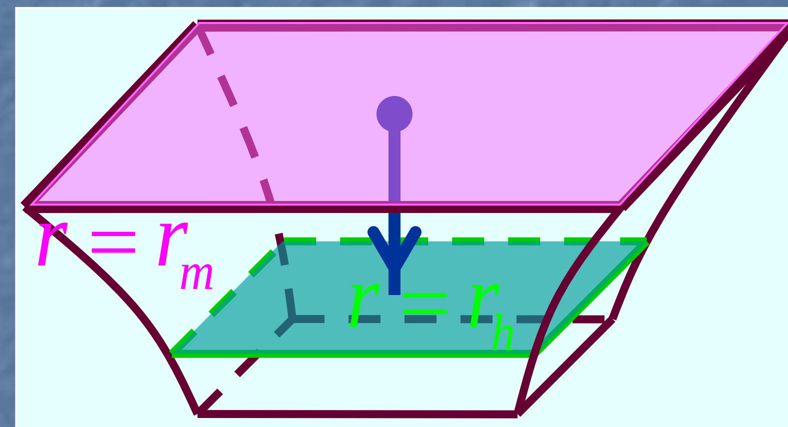
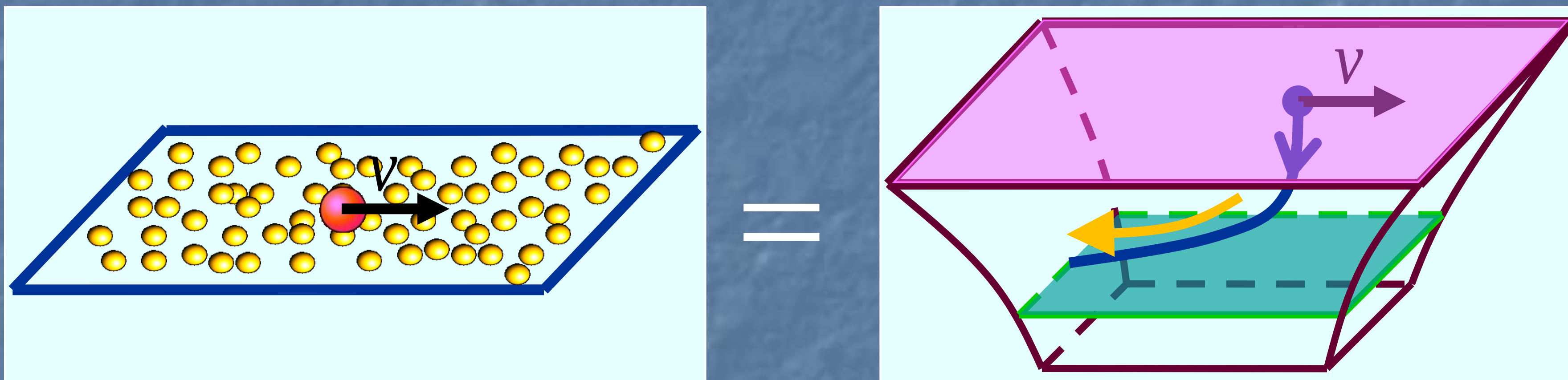


Static quark in SYM plasma $(m \gg T)$ = Vertical string outside black hole in AdS

Application 4: Energy Loss



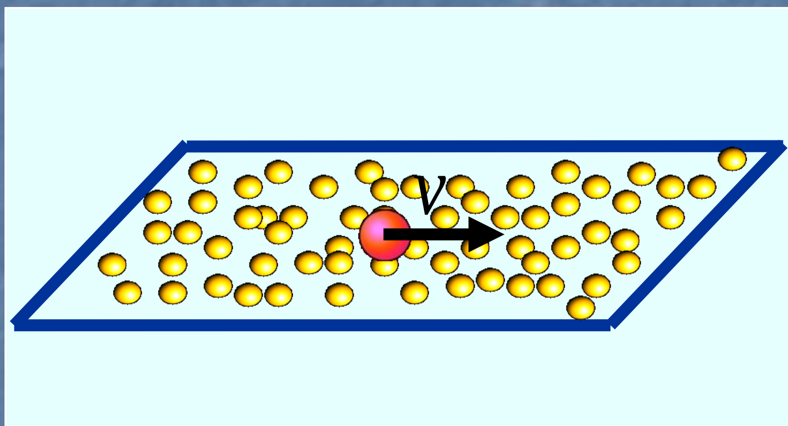
For a moving quark, the string trails behind the endpoint, and acts as an energy sink

i.e., the quark has a 'tail', which gives rise to the expected **drag force**!

Rate of Energy Loss: $$\frac{dE}{dx} = -\frac{\pi}{2}\sqrt{\lambda}T^2 \frac{v}{\sqrt{1-v^2}} = \frac{dp_x}{dt}$$

[Herzog,Karch,Kovtun,Kozcaz,Yaffe; Gubser; Casalderrey-Solana,Teaney]

Application 4: Energy Loss



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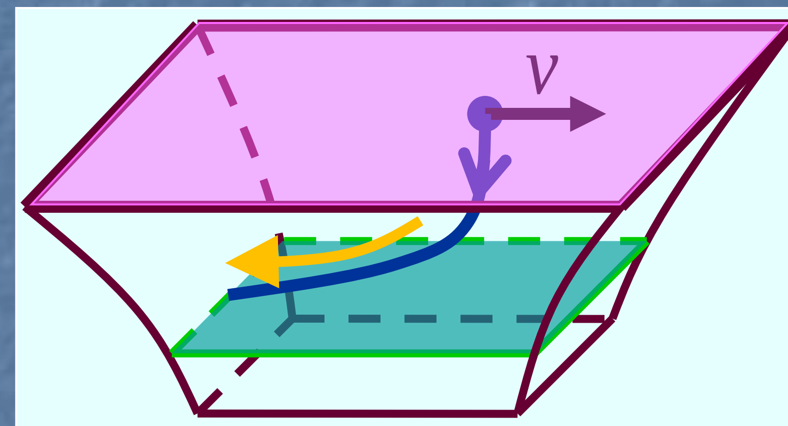
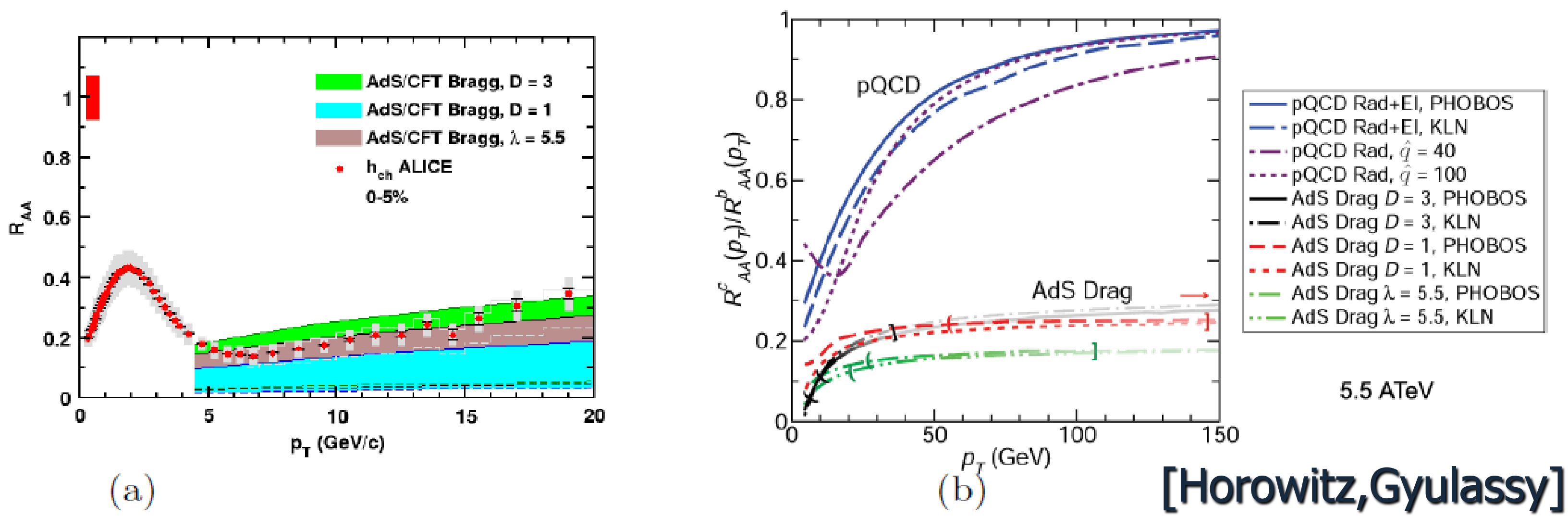


$$\Rightarrow \qquad p_x(t) = p_x(0)\exp\left(-t/t_r\right) \qquad t_r = \frac{2m}{\pi\sqrt{g_{YM}^2 N T^2}}$$

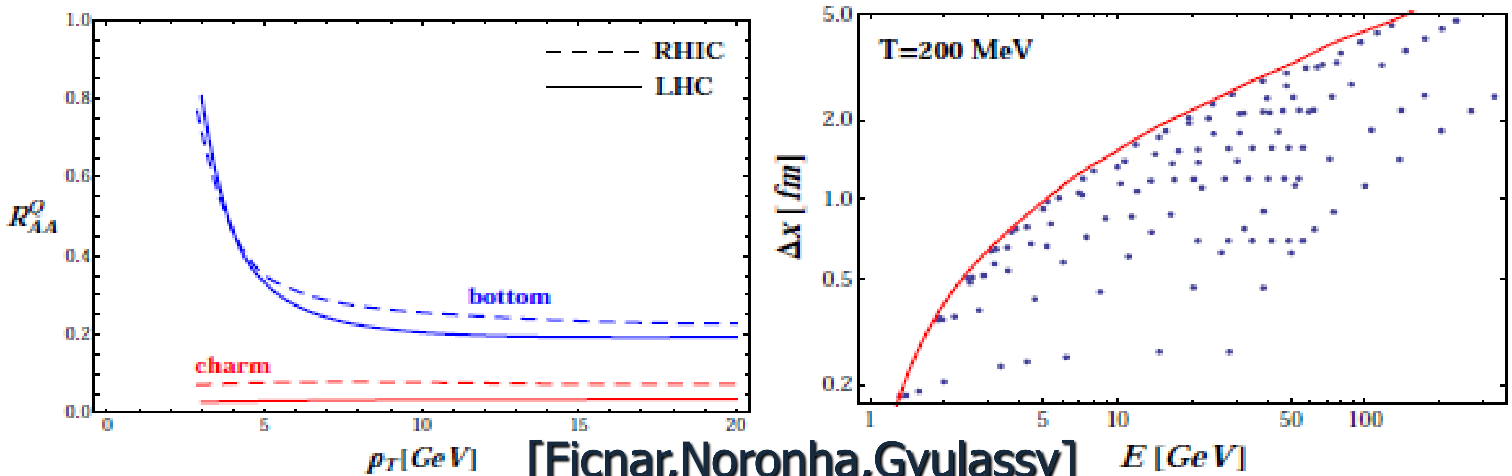
E.g., $t_r(\text{charm}) \approx 0.6 - 2.1\ \text{fm/c}$ [Gubser]

cf. pQCD $t_r(\text{charm}) \approx 4 - 12\ \text{fm/c}$ [van Hees,Rapp]

Results in correct ballpark for RHIC, so people have gone to the trouble of using this trailing string info to construct **phenomenological models**, such as



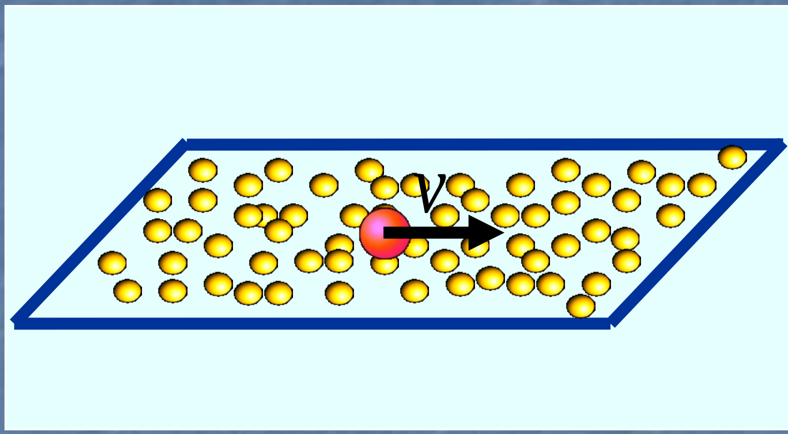
[Horowitz,Gyulassy]



[Ficnar,Noronha,Gyulassy]

CAUTIONARY NOTE: comparisons of results of this type against experimental data do NOT test (at least at present) the gauge/gravity correspondence *per se*, but **gauge/gravity strong-coupling intuition in combination with the specific assumptions of the phenomenological model**

Application 4: Energy Loss



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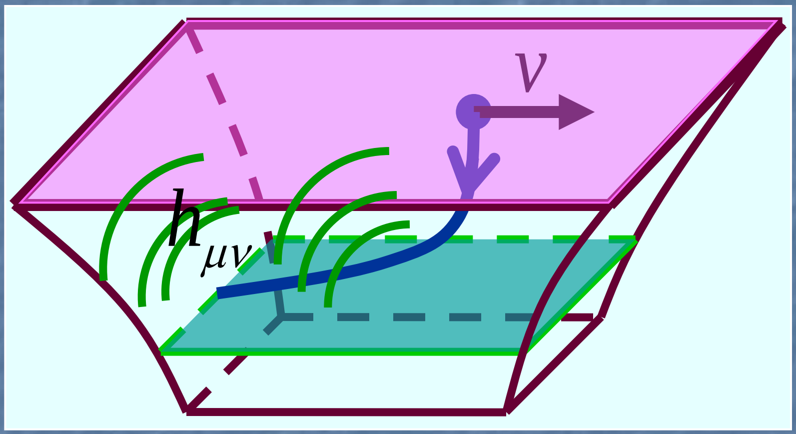


One can determine the energy distribution using

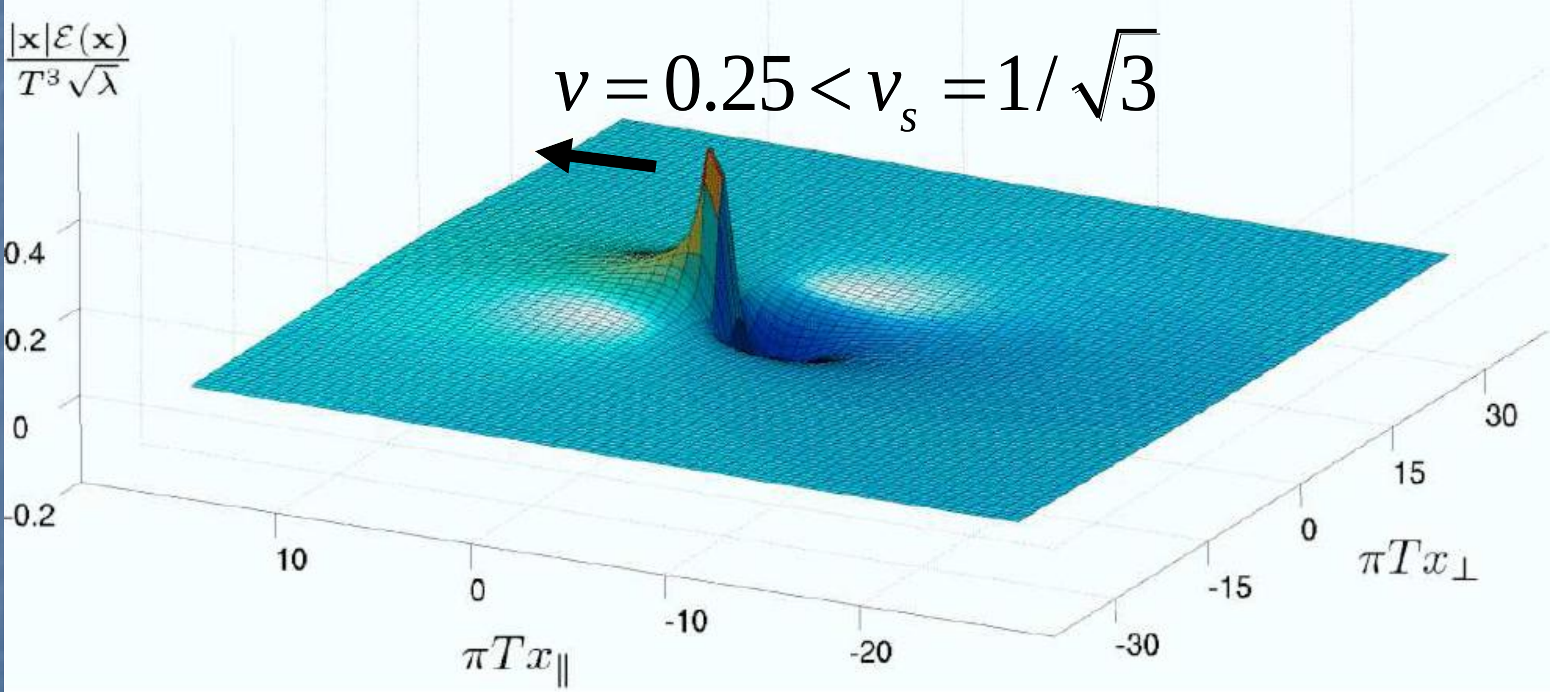
$$\langle T_{\mu\nu}(x) \rangle_{\mathrm{q},v} \quad \leftrightarrow \quad h_{\mu\nu}(x, r = \infty)$$

[Friess,Gubser,Michalogiorgakis;
Friess,Gubser,Michalogiorgakis,Pufu;
Yarom; Gubser,Pufu; Gubser,Pufu,Yarom;
Chesler,Yaffe; Noronha,Torrieri,Gyulassy;
Betz,Gyulassy,Noronha,Torrieri; etc.]

Application 4: Energy Loss

Energy density in wake generated by the quark

[Gubser,Pufu,Yarom; Chesler,Yaffe]



From: Chesler,Yaffe, arXiv:0706.0368

Application 4: Energy Loss

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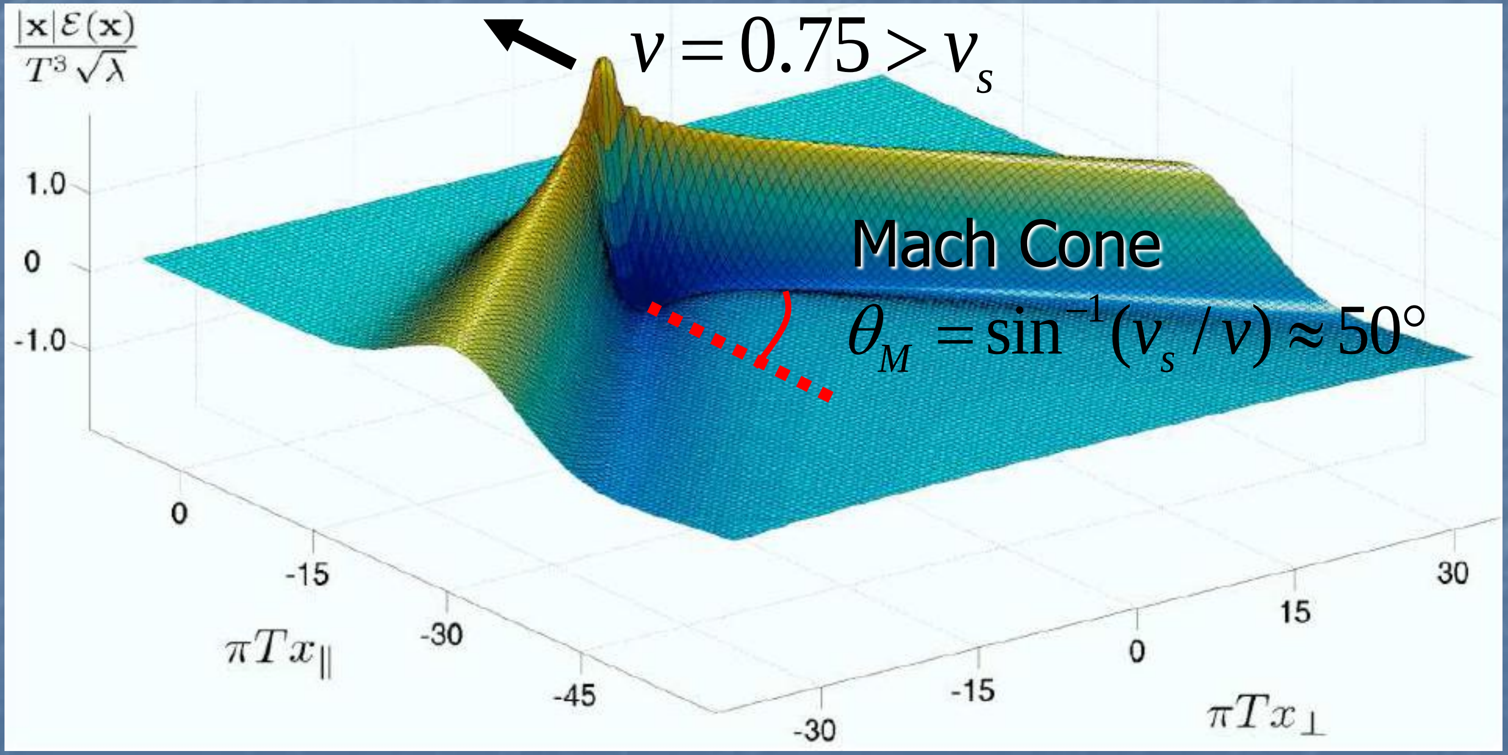
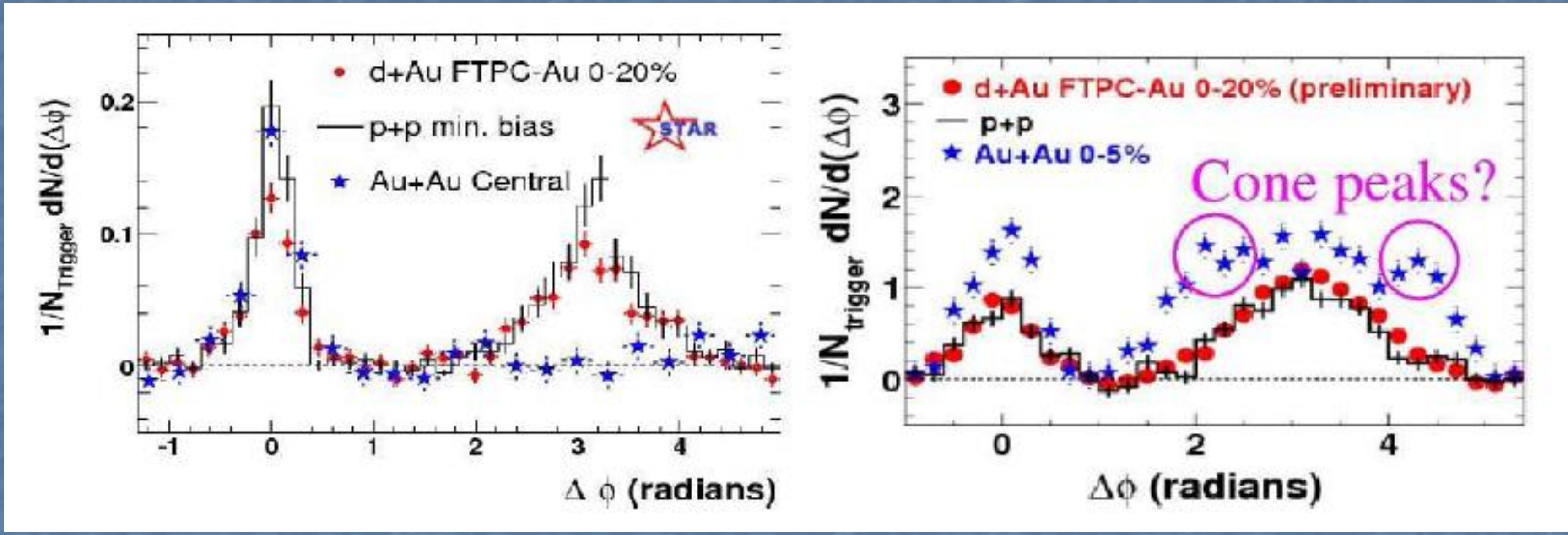


From: Chesler, Yaffe, arXiv:0706.0368

Application 4: Energy Loss

This has also been put to use in phenomelogical models, e.g.,

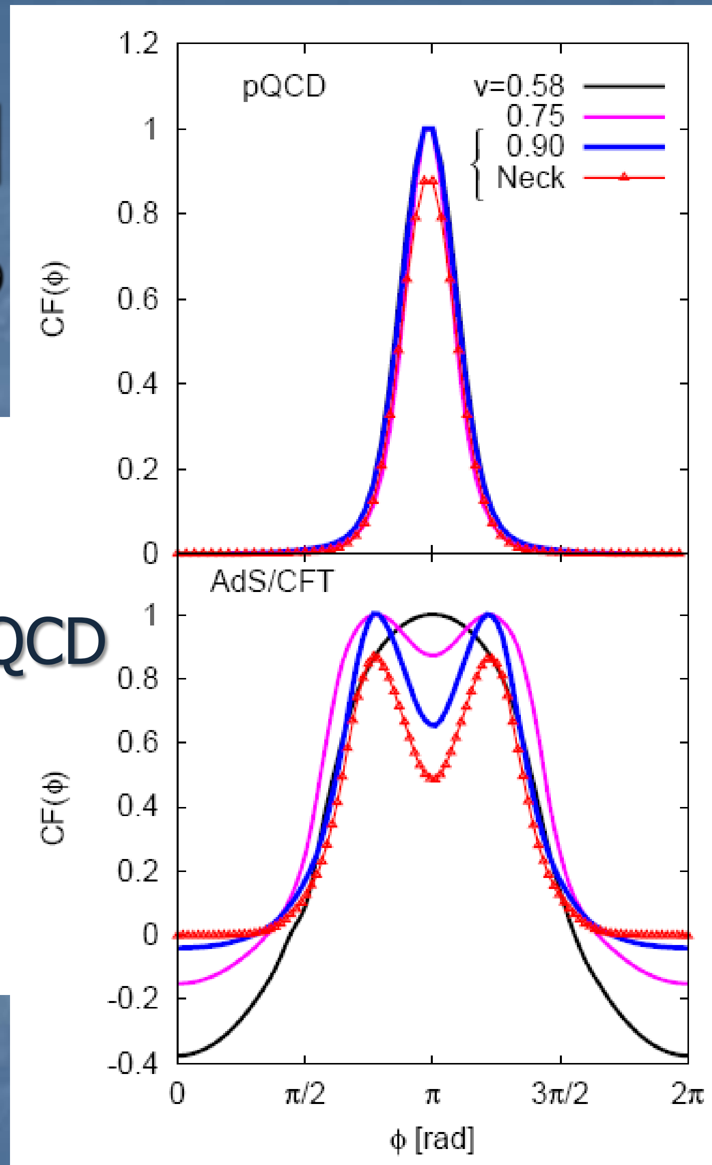


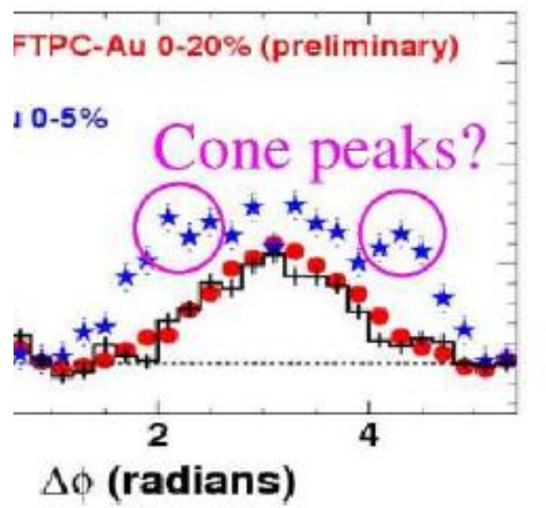
From: Betz,Gyulassy,Noronha,Torrieri arXiv:0807.4526

Appl gy Loss

This has also omelogical models, e.g.,

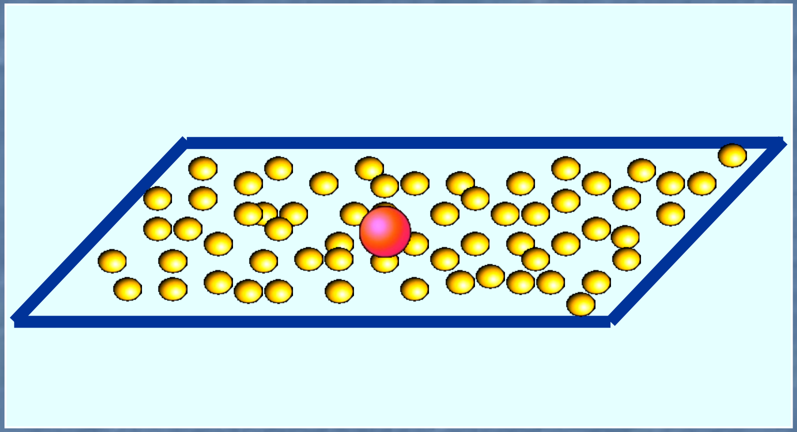
Result from perturbative QCD vs. AdS/CFT:





From: Betz,Gyulassy,Noronha,Torrieri arXiv:0807.4526

Application 5: Brownian Motion



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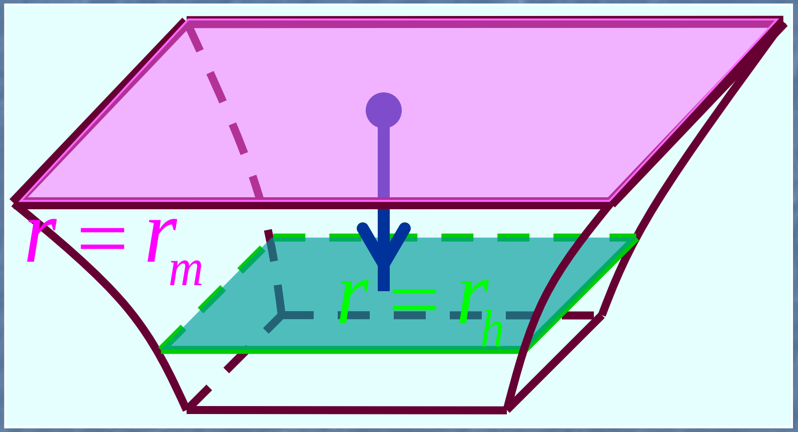
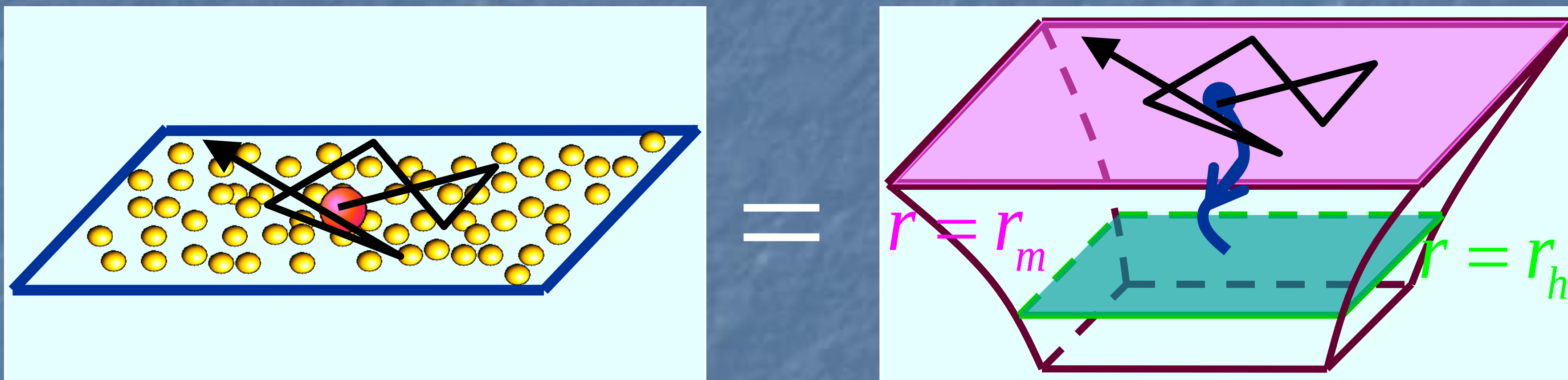


Static Quark in SYM plasma $(m \gg T)$ = Vertical string outside black hole in AdS

Expert the quark to experience thermal fluctuations (Brownian motion)…

But who makes string endpoint jump around?

Application 5: Brownian Motion



- **Hawking radiation** emitted by the black hole (on string 'worldsheet')!

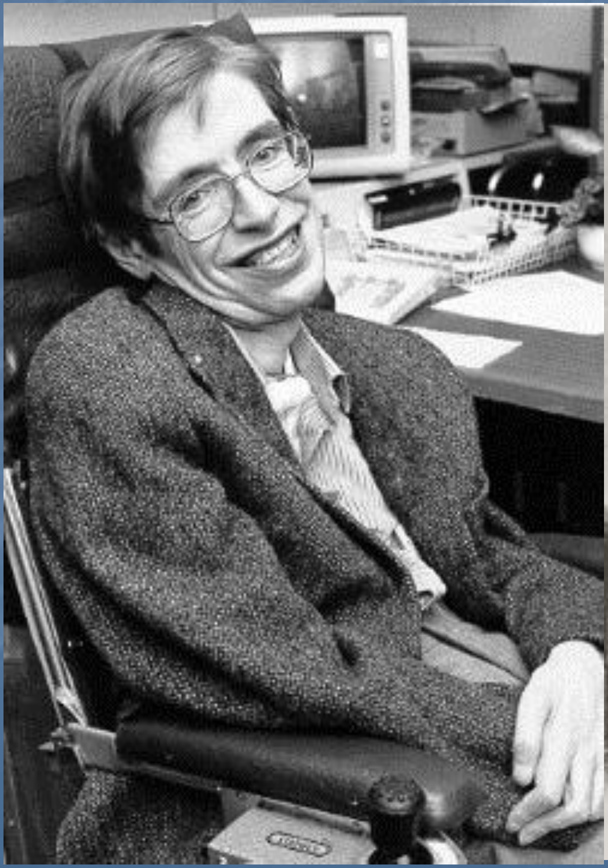
String endpoint obeys a generalized Langevin eqn.

$$m\ddot{x} + \int dt'\,\eta(t,t')\dot{x}(t') = \xi(t), \quad \langle \xi(t)\xi(t') \rangle = \kappa(t,t')$$

[de Boer,Hubeny,Rangamani,Shigemori; Son,Teaney; Casalderrey,Teaney; Giecold,Iancu,Mueller; Atmaja,de Boer,Shigemori; Cáceres,Chernicoff,AG,Pedraza]

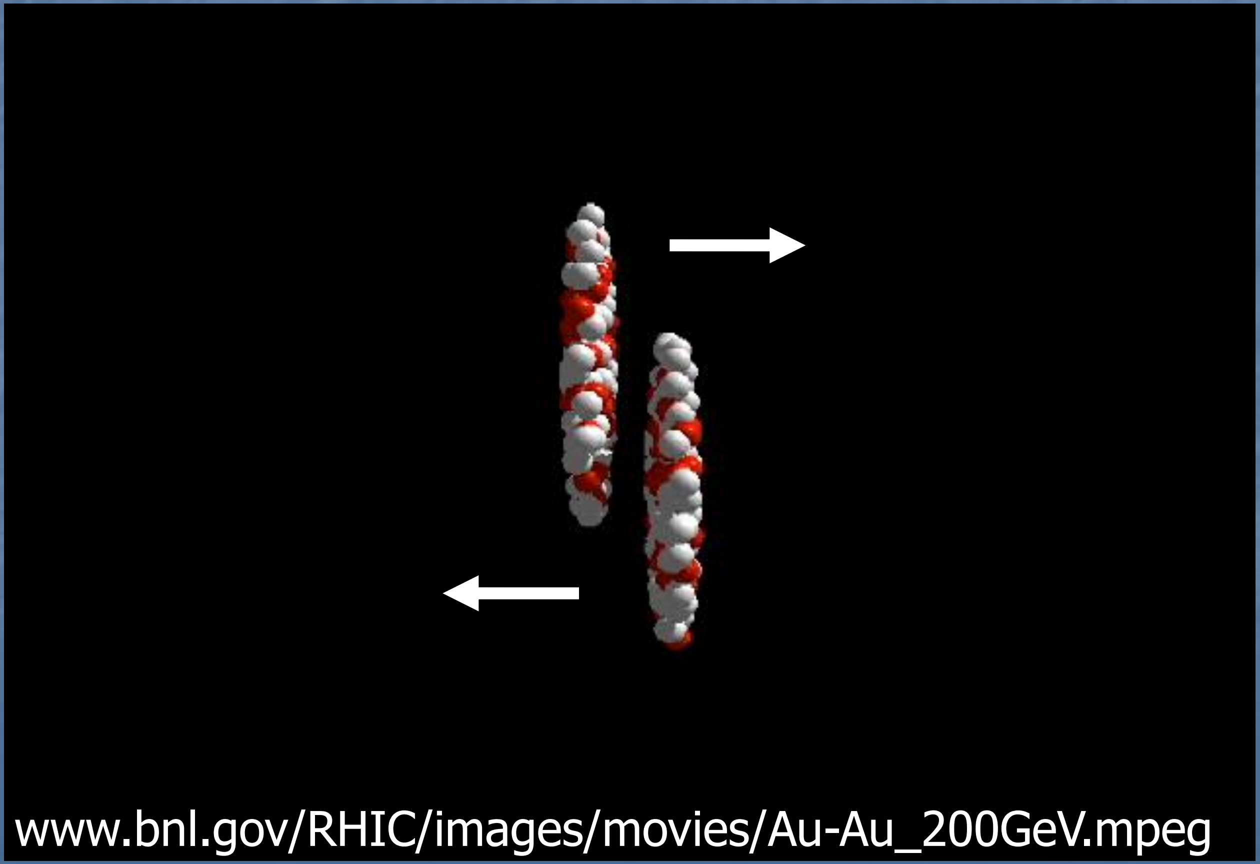
So, in the gauge/gravity correspondence

Hawking = Brown!!



Application 6: Thermalization

Recall QGP production in heavy ion collisions:



Application 6: Thermalization

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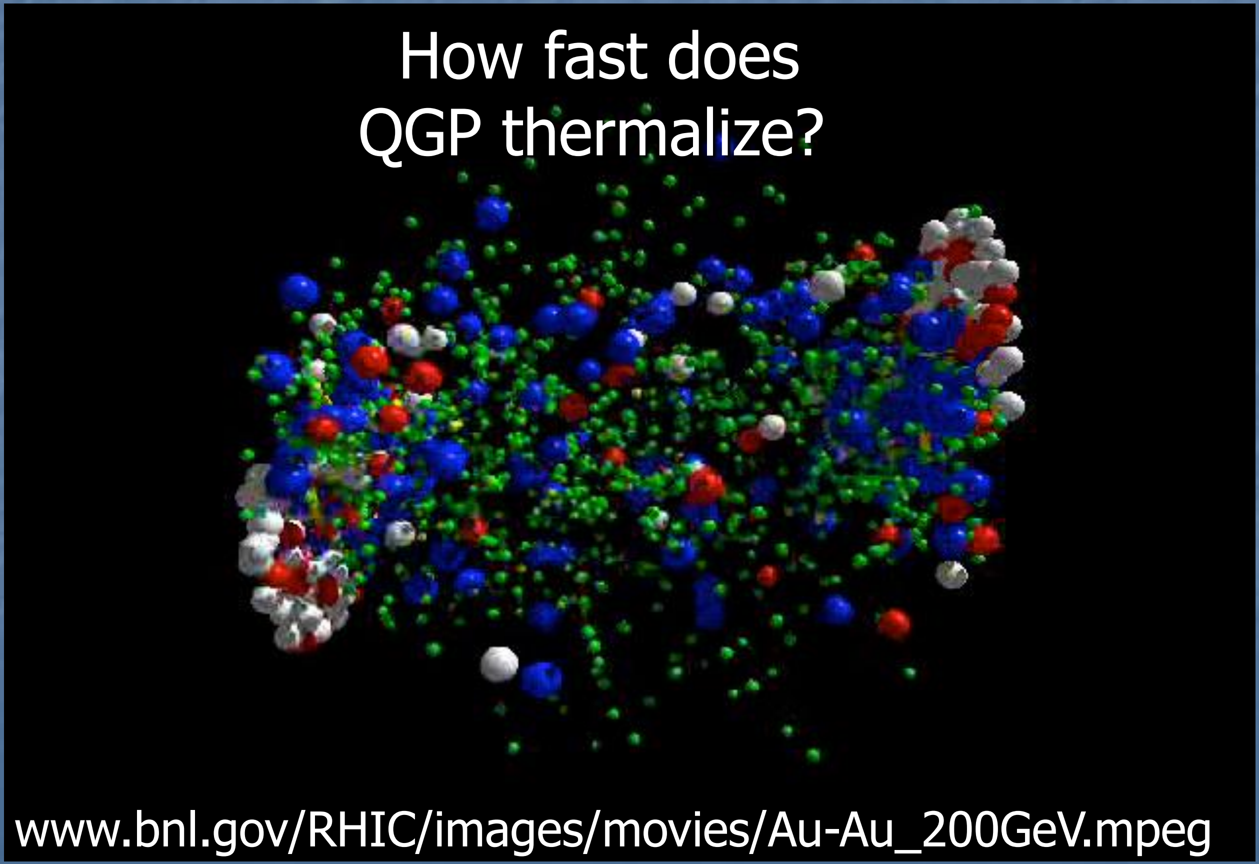
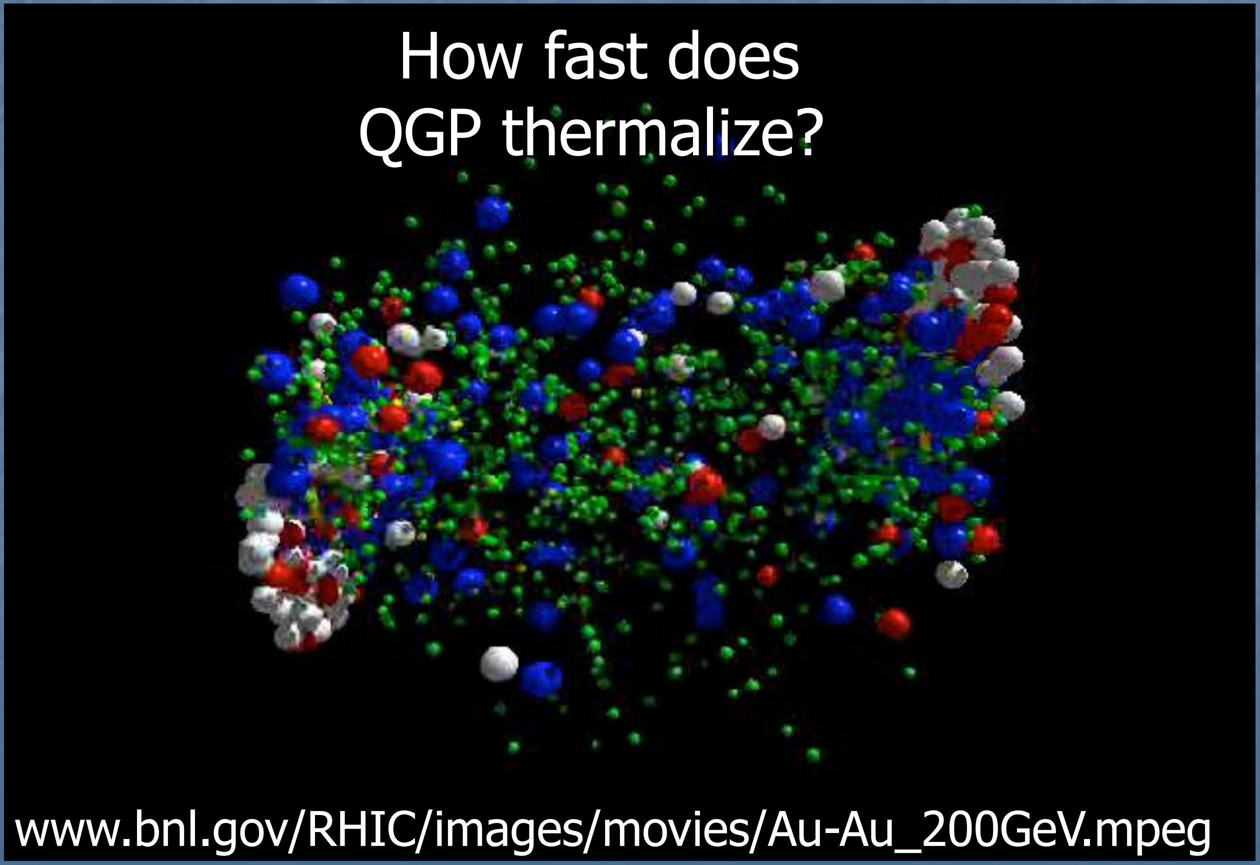
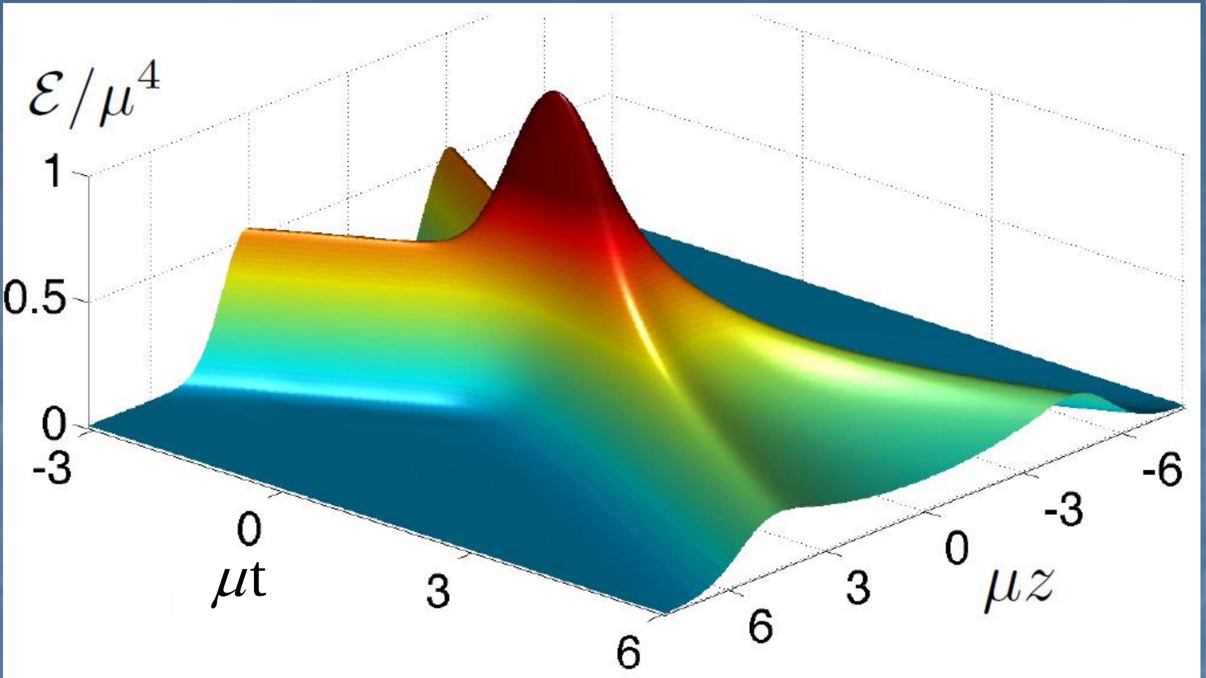


Application 6: Thermalization

Formation of Thermal Plasma in SYM = **Formation** of Black Hole in AdS

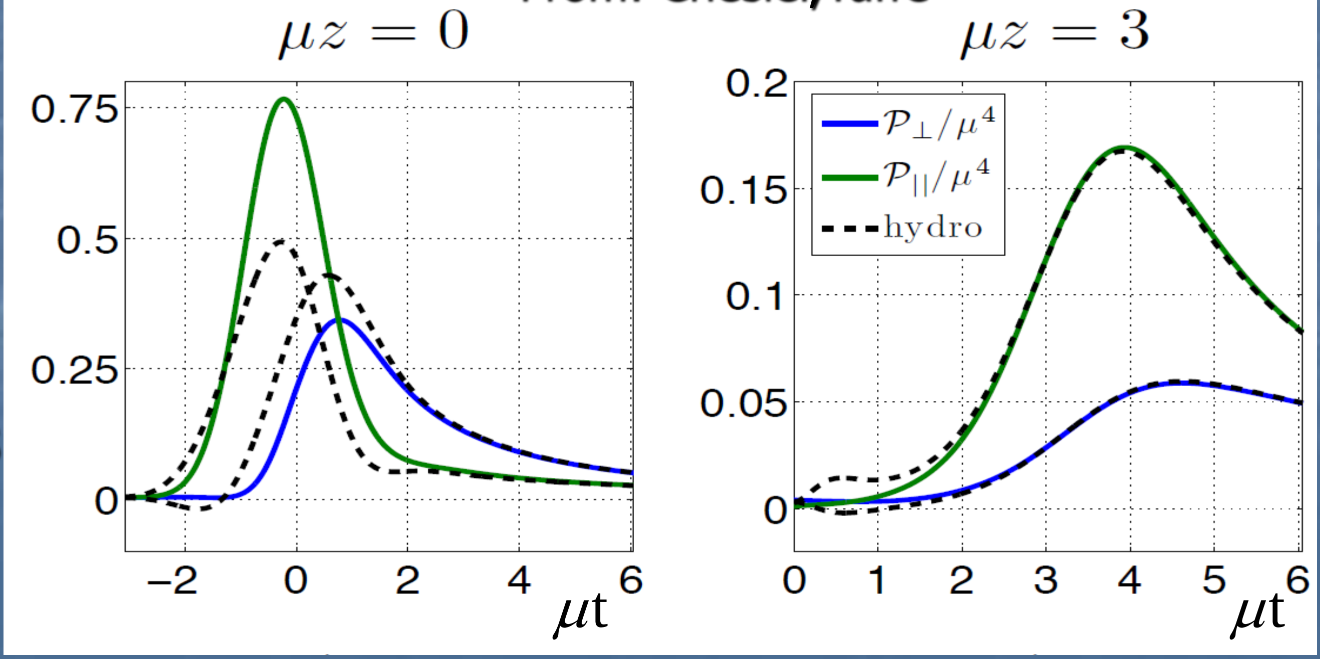


Energy/area in collision of 2 infinite walls (w/Gaussian profile and amplitude μ):



From: Chesler,Yaffe

Resulting longitudinal and transverse pressures, vs. hydrodynamics



Application 6: Thermalization

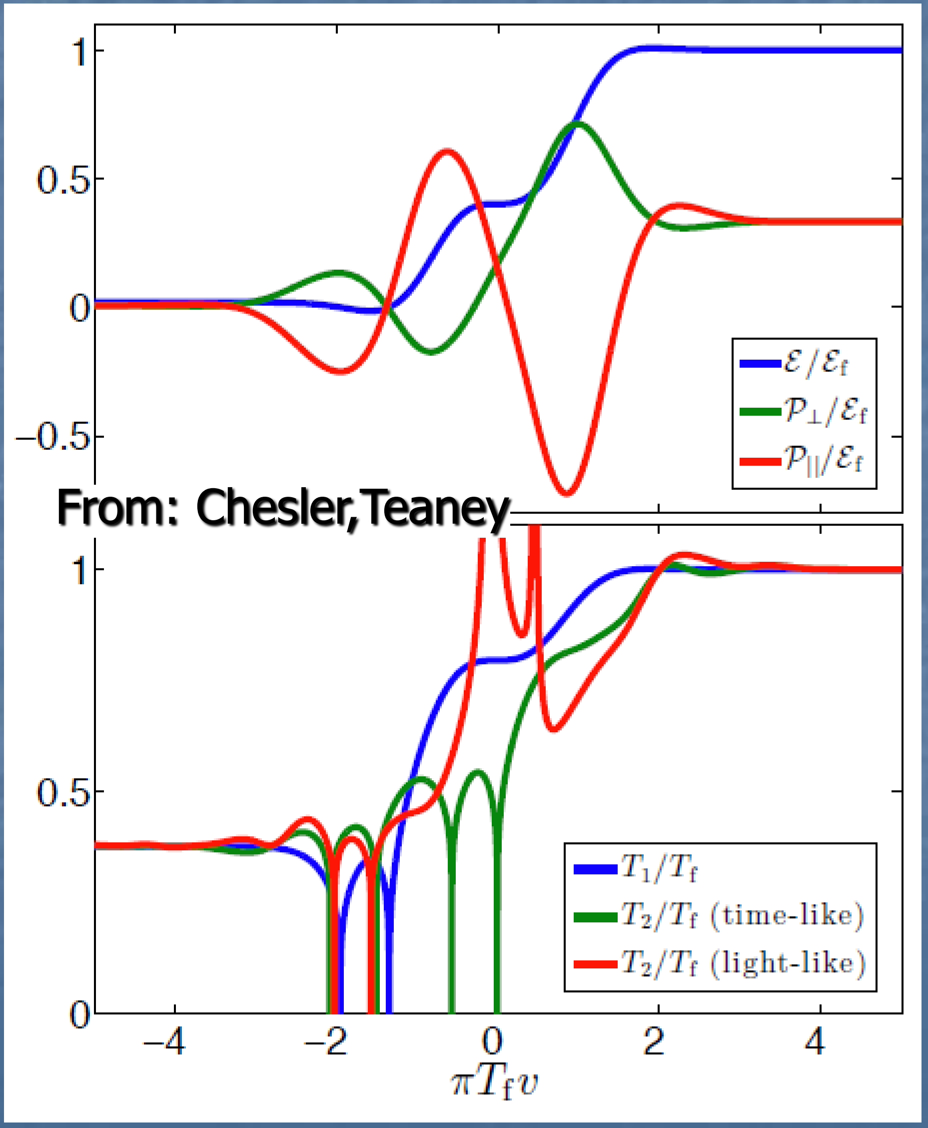
UV modes thermalize **before** IR modes

Relevant time scale ~0.35 fm/c at RHIC

[Balasubramanian,Bernamonti,deBoer,Copland,Craps,Keski-Vakkuri,Müller, Schäffer,Shigemori,Staessens; Chesler,Yaffe; Chesler,Teaney; Gubser,Pufu,Yarom; Grumiller,Romatschke; Kovchegov,Taliotis; Albacete,Kovchegov,Taliotis; Álvarez-Gaume,Gómez,SabioVera, Tavanfar,Vázquez-Mozo; Garfinkle,PandoZayas,Reichmann; Das; Heller,Janik,Witaszcyk; Ali-Akbari,Ebrahim; Galante,Schvellinger; Cáceres,Kundu; Baier,Stricker,Taanila,Vuorinen; Erdmenger,Lin; Buchel,Lehner,Myers; Steineder,Stricker,Vuorinen; etc.]

Application 6: Thermalization

But, distinction between (earlier) "**hydrodization**" **time** (time when hydrodynamics is valid) and (later) **thermalization time** (when temperature is well defined):


From: Chesler,Teaney

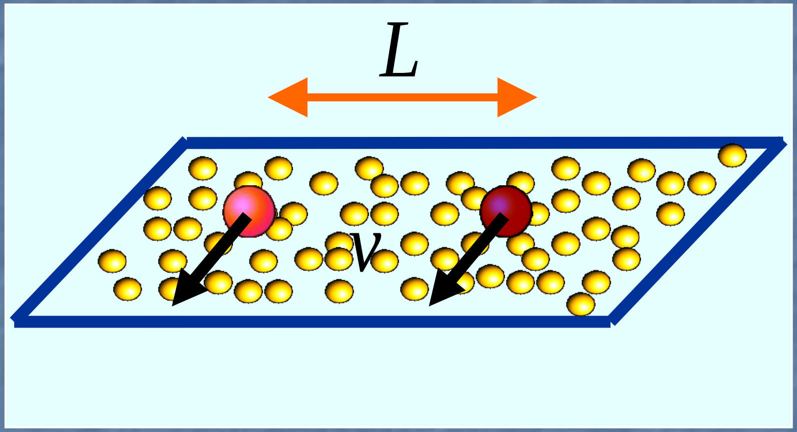
Many Other Applications…

- Screening / Meson Melting [Liu,Rajagopal,Wiedemann; Chernicoff,García,AG; Peeters,Sonnenschein,Zamaklar; Cáceres,Natsuume,Okamura; Mateos,Myers,Thomson; etc.]
- Limiting velocity [Argyres,Edalati,Vázquez-Poritz; Gubser; Casalderrey,Teaney; Mateos,Myers,Thomson; Ejaz,Faulkner,Liu,Rajagopal,Wiedemann; etc.]
- Jet quenching parameter $\hat{q}$ [Liu,Rajagopal,Wiedemann; etc.]
- Light parton energy loss [Chesler,Jensen,Karch,Yaffe; Gubser,Gulotta,Pufu,Rocha; Arnold,Vaman, etc.]
- Expanding plasma [Janik,Peschanski; Shuryak,Sin,Zahed; Nastase; Nakamura,Sin; Friess,Gubser,Michalogiorgiakis,Pufu; etc.]
- Anisotropic plasma [Mateos,Trancanelli; etc.]
- Cherenkov radiation of mesons [Casalderrey,Mateos; etc.]
- Etc.

Conclusions

1) The **holographic correspondence** establishes a very surprising **equivalence** between field theories and gravity (usually string) theories
2) This is by now an **established tool**, that has proved **useful** to understand the behavior of some theories that are **strongly-coupled solvable toy models of QCD, superconductors, non-Fermi liquids, etc.**
3) There are several **limitations**: we don't yet know the complete dictionary, nor can we compute directly in real-world systems
4) This correspondence gives us **the best definition we have to date of string theory** and **quantum gravity**
5) **A lot remains to be done!**

Application #: Screening Length



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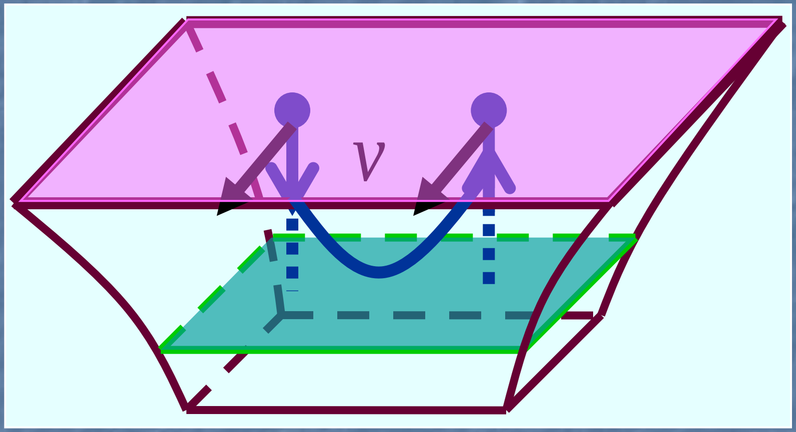


Meson moving through SYM plasma

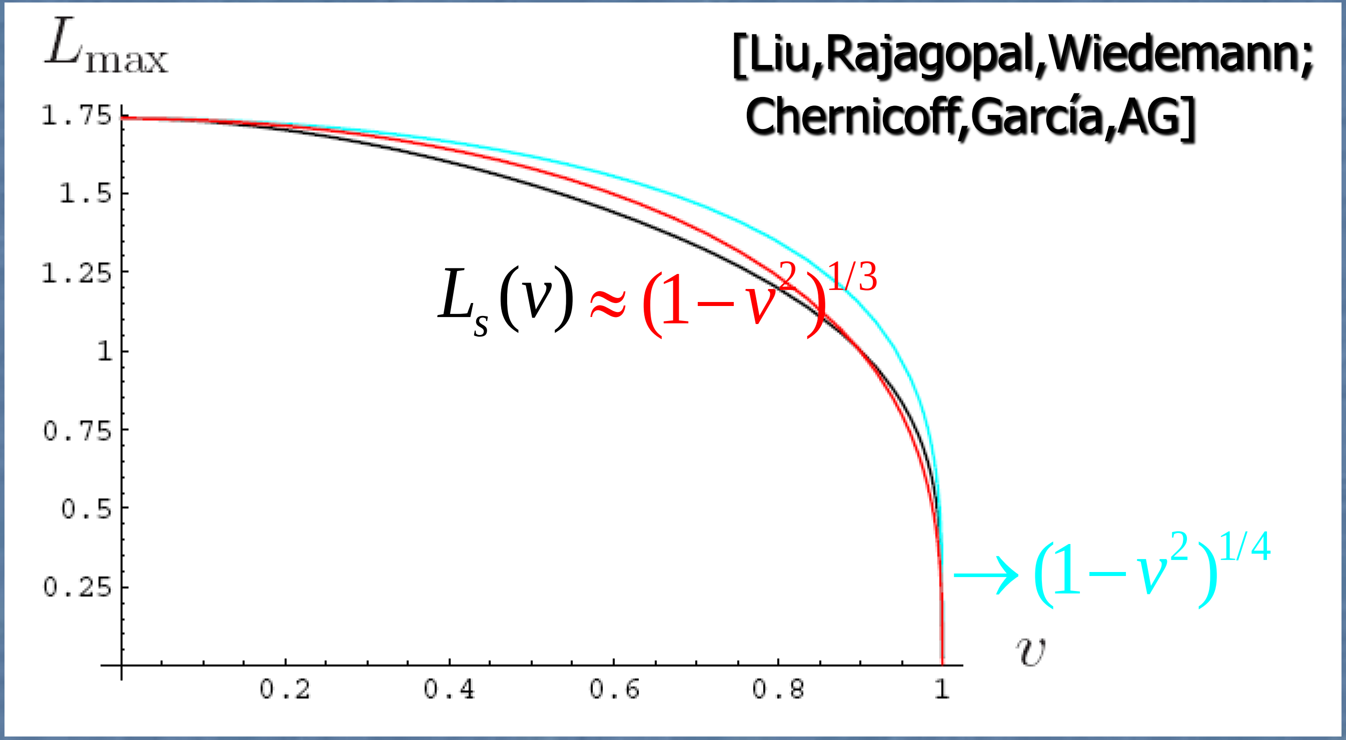
U-shaped string moving near black hole in AdS

Plasma screens potential, and makes it harder for quark and antiquark to form a bound state

$$V_{q\bar{q}}^{T}(L, v)$$

[Chernicoff,García,AG; Liu,Rajagopal,Wiedemann]

Application #: Screening Length



Possibly relevant for J/psi suppression [Matsui,Satz]

$$\Rightarrow T_{\text{dis}} \propto (1-v^2)^p$$

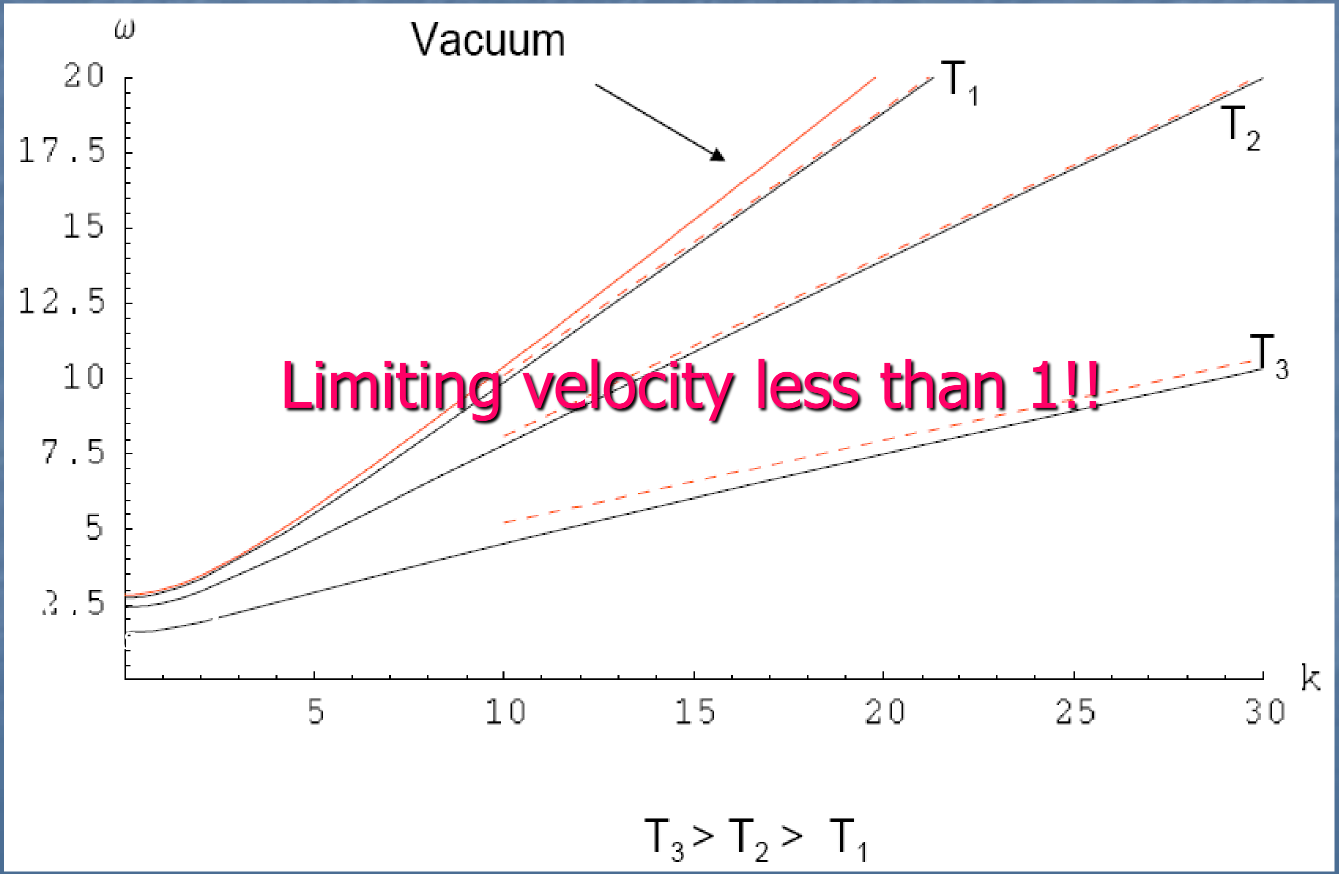
[Liu,Rajagopal,Wiedemann; Cáceres,Natsuume,Okamura]

(Larger suppression for charmonium with larger p_T)

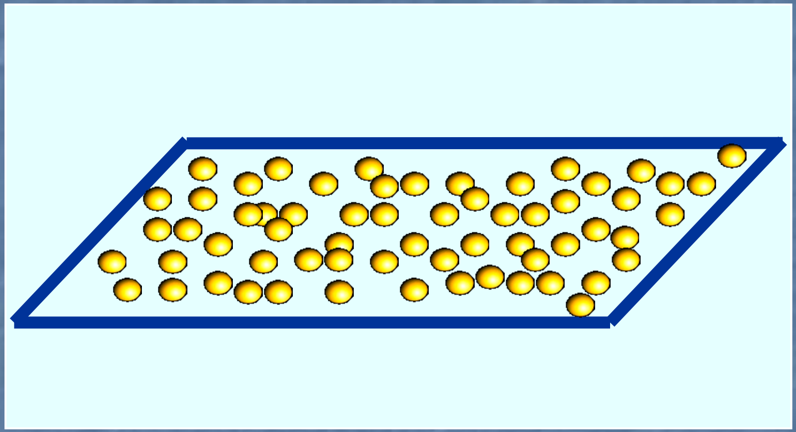
Application #: Limiting Velocity

Meson dispersion relations at increasing $T < T_{\mathrm{fun}}$:

[Mateos,Myers,Thomson; Ejaz,Faulkner,Liu,Rajagopal,Wiedemann]



Application #: Limiting Velocity



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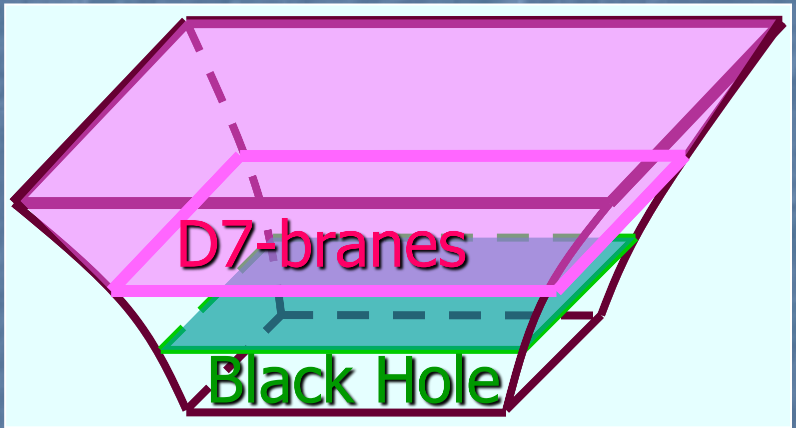
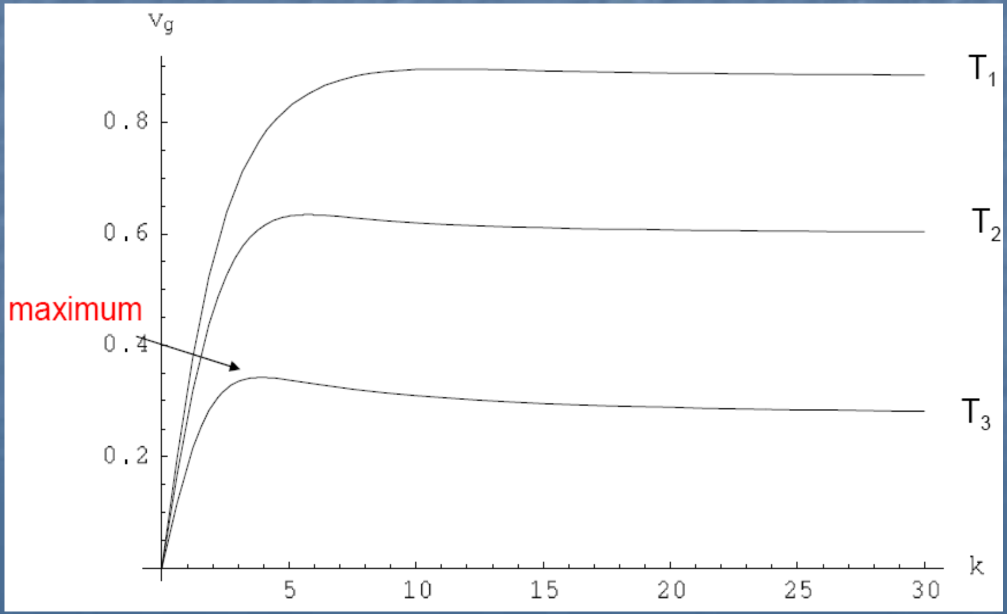




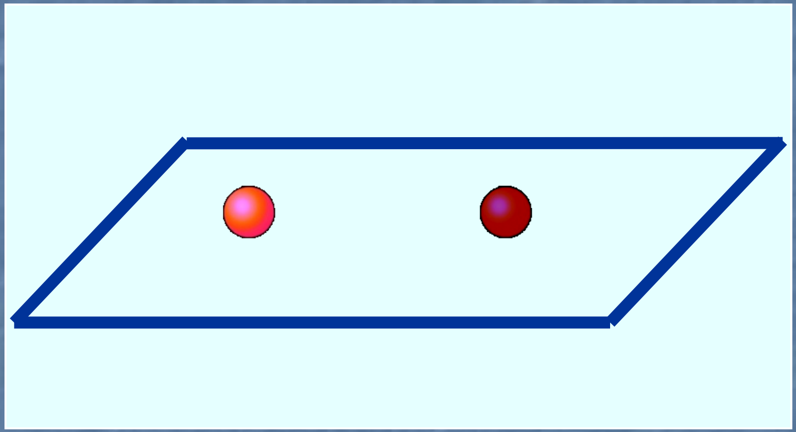
Origin: local speed of light at edge of D7-branes,

$$v_{\max} = \sqrt{1-(r_h / r_m)^4}$$

$$\approx 1-\left(\sqrt{\lambda} T / m_q\right)^4$$

[Argyres,Edalati,Vázquez-Poritz]

Application #: Meson Melting



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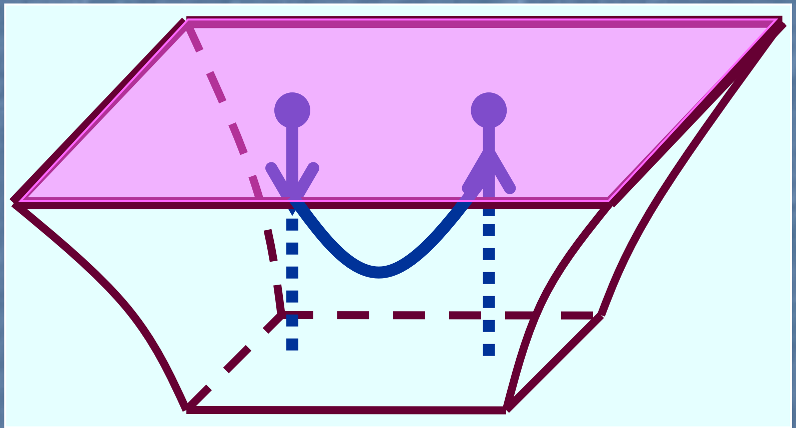


Can also determine **microscopic** meson spectrum, e.g.

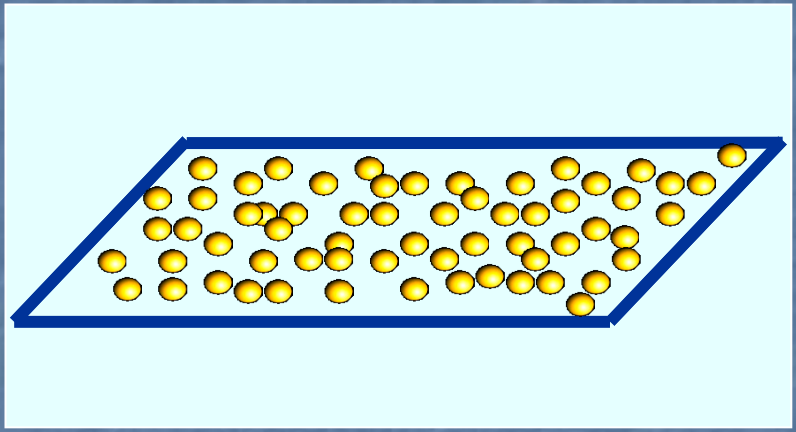
$$M_s = \frac{2\pi m_q}{\sqrt{g_{YM}^2 N}} \sqrt{(n+l+1)(n+l+2)}$$ for scalar mesons

[Kruczenski,Mateos,Myers,Winters]

Notice that $M_s \ll m_q$: **mesons** are lightest d.o.f.

(Can in fact recover quark as a soliton made of mesons!)

Application #: Meson Melting



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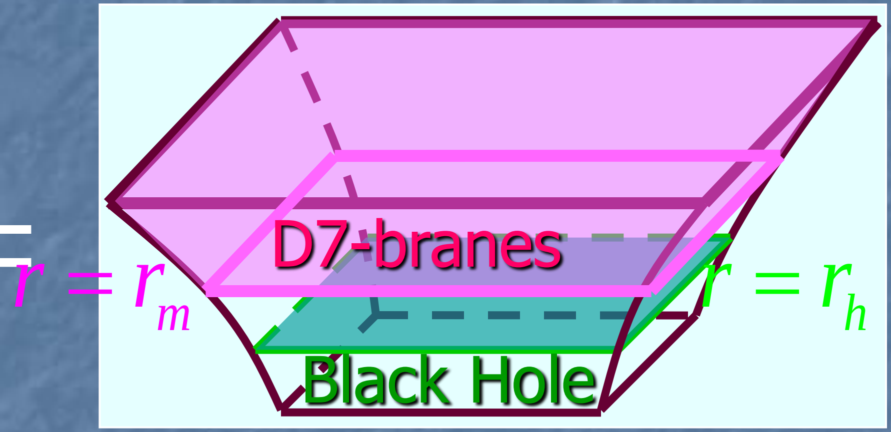


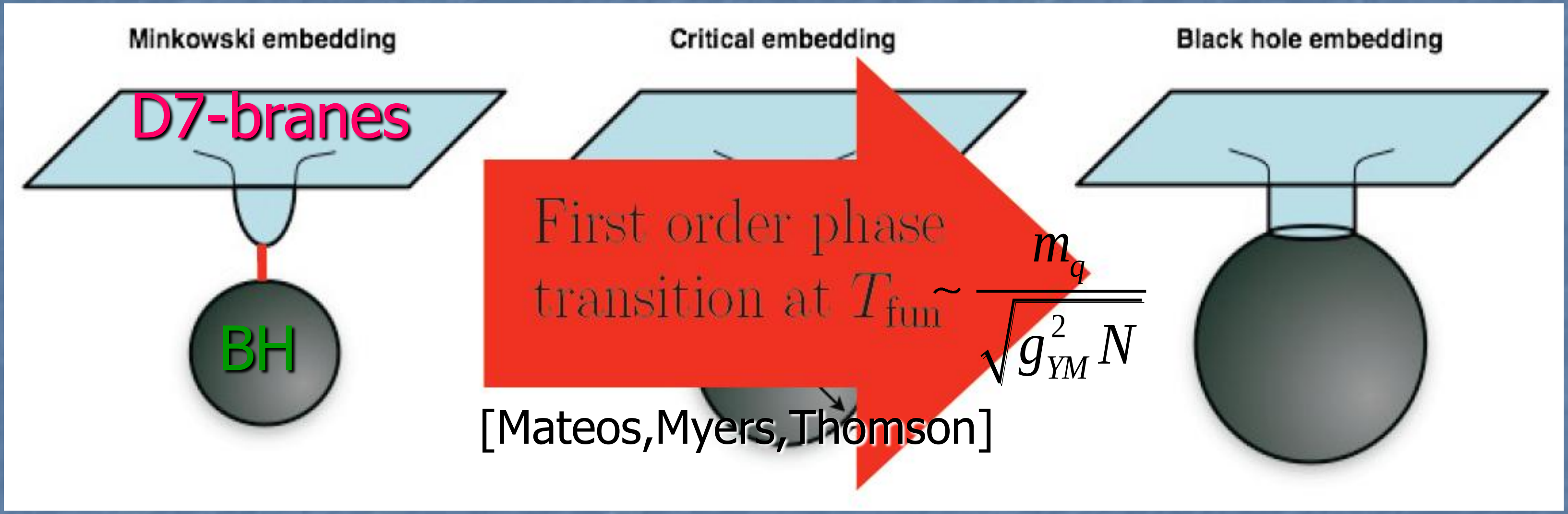
r_m related to quark mass m

r_h proportional to temperature T

For large enough T/m, the D7-branes end INSIDE BH

Application #: Meson Melting

View omitting SYM directions but including S^5 :



Discrete meson spectrum

$$M_{\rm mes} \sim T_{\rm fun}$$

(stable: survive deconfinement)

+ Massive quarks

Continuous spectrum...
with NO quasi-particles!!