Quarkonium dissociation by anisotropy in a strongly coupled plasma

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Based on 1208.2672 (and 1202.3696) in collaboration with
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Plan for the talk

• Motivation

• The AdS/CFT toolkit

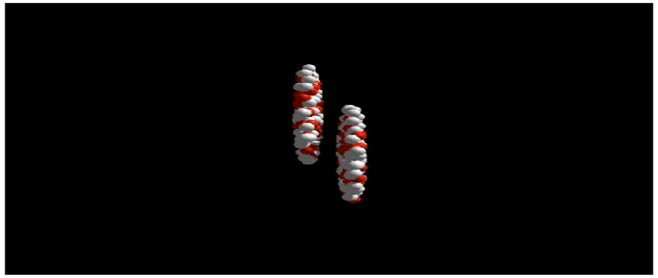
• Quarkonium physics

• Conclusions

Motivation

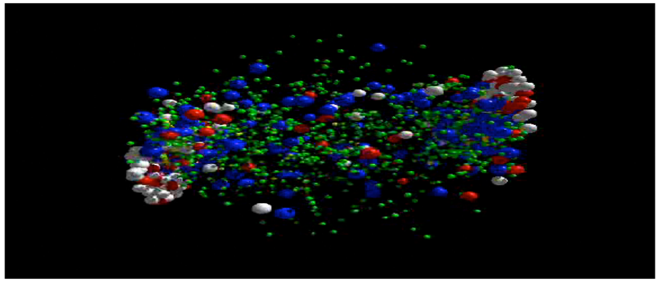
For the creation of the quark gluon plasma

400 nucleons go in



Energy of CM 200 GeV

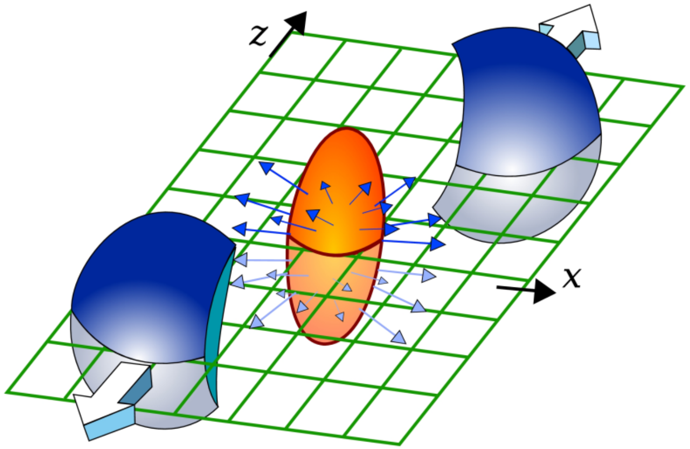
8000 hadrons are produced



1-10 GeV per hadron

Motivation

The time evolution of the quark gluon plasma



$\tau_{\rm iso} \lesssim 1{\rm fm}$

[Romantschke et al; Mrowczynski et al.]

$z \equiv$ longitudinal direction

$x, y \equiv$ transverse direction

Collision — $\tau_{\rm out}$ — $\tau_{\rm iso}$ →

Far from equilibrium	Anisotropic hydrodynamics	Isotropic hydrodynamics
	$P_\perp \neq P_\parallel$	$P_\perp = P_\parallel$

Motivation

Things we know about the quark gluon plasma

→ After a very short period of time the system is in thermal equilibrium

$$\sim 200 - 400\mathrm{MeV}$$

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→ It is a strongly coupled system (ideal fluid + small η/s)

Perturbative methods are inapplicable and lattice QCD is not well suited to study real-time dynamics.

Motivation

Things we know about the quark gluon plasma

$\longrightarrow$ After a very short period of time the system is in thermal equilibrium

$$\sim 200 - 400 \mathrm{MeV}$$

$\longrightarrow$ It is a strongly coupled system (ideal fluid + small η/s)

Perturbative methods are inapplicable and lattice QCD is not well suited to study real-time dynamics.

$\longrightarrow$ Some observables are sensitive to the presence of an anisotropy

- Quarkonium physics (J/Ψ) [Dumitru et al.; Philipsen et al.]
- Momentum broadening [Dumitru et al.; Mehtar-Tani; Romantschke et al.]

Motivation

About quarkonium in heavy ion collisions:

→ Quarkonium refers to charm-anticharm mesons (J/Ψ, Ψ' , χ_c , ...) and bottom-antibottom mesons (Υ, Υ', ...)

1s state

Motivation

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→ Quarkonium refers to charm-anticharm mesons (J/Ψ, Ψ' , χ_c , ...) and bottom-antibottom mesons (Υ, Υ', ...)

→ J/Ψ mesons survive as bound states in a hot medium up to some dissociation temperature T_d that is higher than the deconfinement temperature T_c (lattice predicts: $T_d(J/\Psi) \simeq 2T_c$).

Motivation

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- RHIC data: J/Ψ - suppression in nucleus-nucleus collisions when compared to proton-proton collisions.

J/Ψ mesons are screened in the quark gluon plasma

Motivation

It is important to understand how they are screened by the QGP

→ What is the effect of the anisotropy?

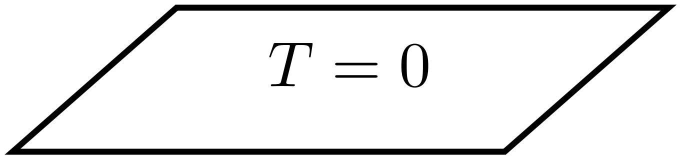
→ They might be moving with significant transverse momentum through the hot medium, what is the effect of such “wind”?

We will use the AdS/CFT correspondence to address this questions

AdS/CFT toolkit

$\mathcal{N} = 4\ \text{SYM}$ $=$ Type IIB on $AdS_5 \times S^5$

on Minkowski 3+1



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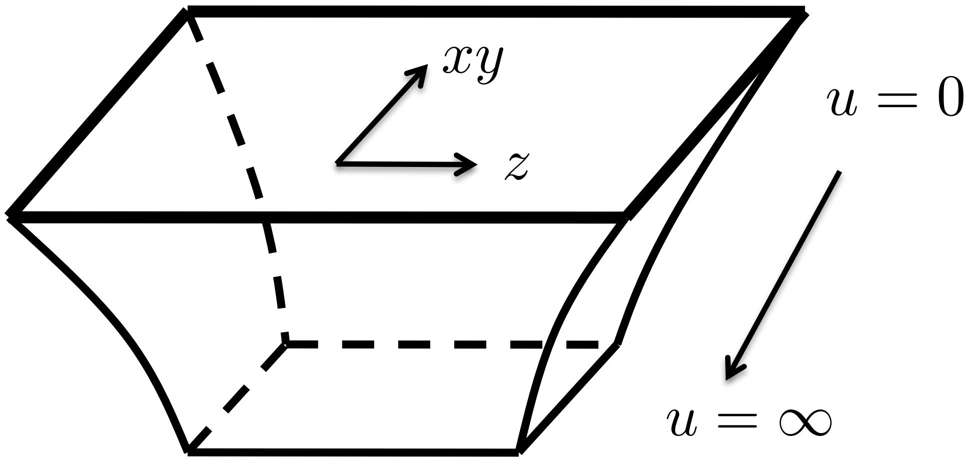
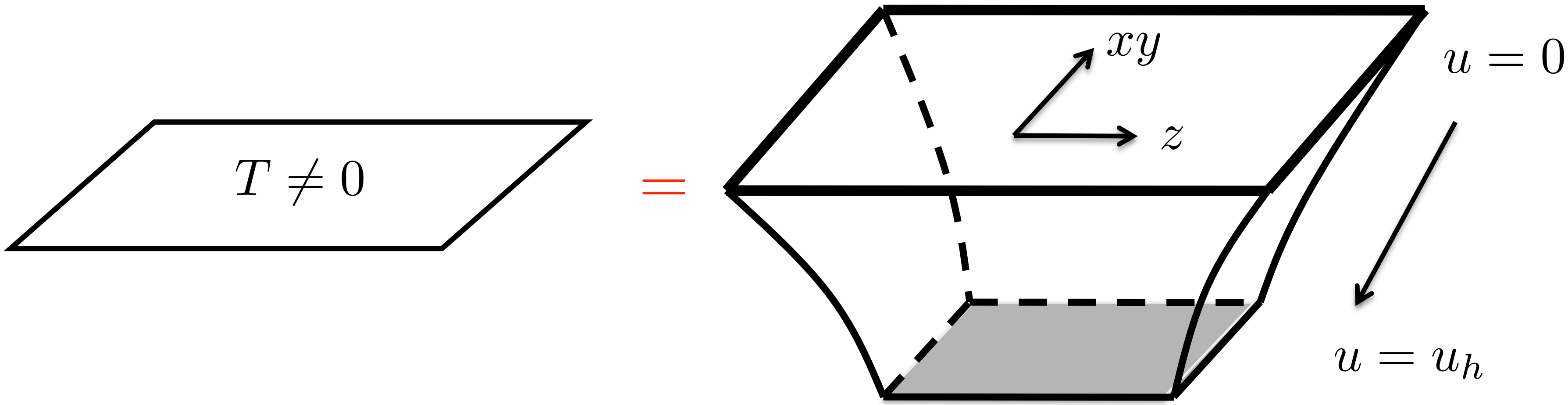


$$\lambda \equiv \frac{L^4}{l_s^4} = g^2_{\text{YM}} N_c$$

$$ds^2 = \frac{L^2}{u^2}\left[-dt^2 + d\vec{x}^2 + du^2 \right]$$

AdS/CFT toolkit

$\mathcal{N}=4$ SYM at finite temperature $=$ Schwarzschild AdS black hole



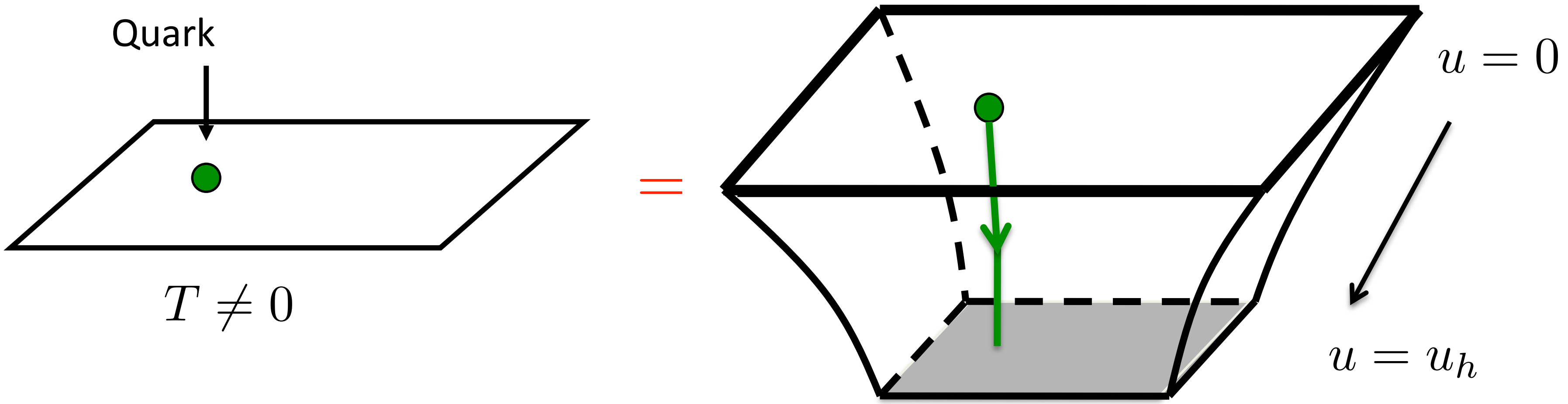
$$ds^2 = \frac{L^2}{u^2}\left[-f(u)dt^2 + d\vec{x}^2 + \frac{du^2}{f(u)} \right]$$

with $f(u) = 1 - \frac{u^4}{u_h^4}$

Note: we will refer to this metric as the isotropic metric

AdS/CFT toolkit

External quark $=$ Fundamental string

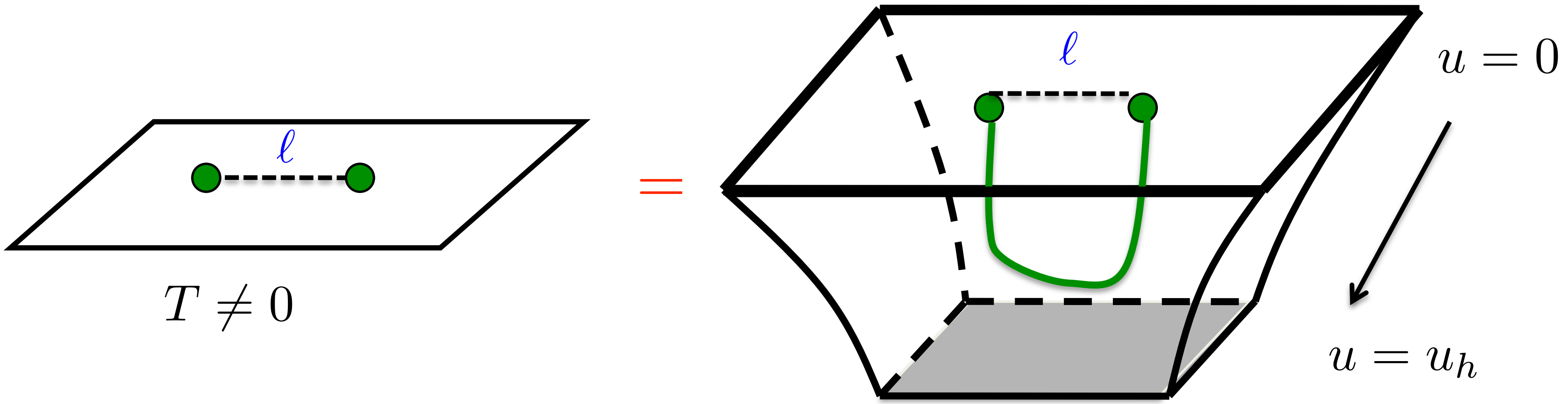


• A fundamental string extending from the boundary at $u = 0$ to the horizon corresponds to an infinitely massive quark.

• The string endpoint represents the quark, while the rest of the string codifies the profile of the gluonic field

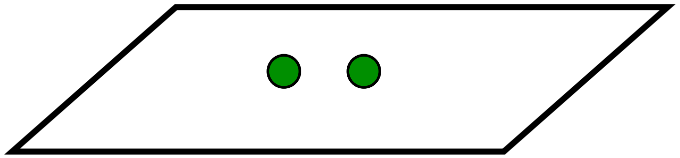
AdS/CFT toolkit

meson (bound state) $=$ U-shaped string



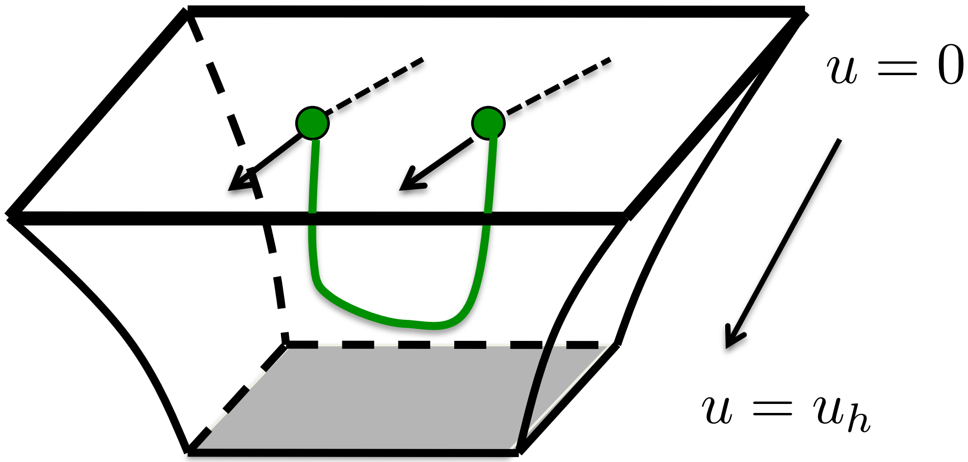
AdS/CFT toolkit

meson (bound state) moving at constant velocity $=$ U-shaped string moving at constant velocity



$T \neq 0$

$=$



AdS/CFT toolkit

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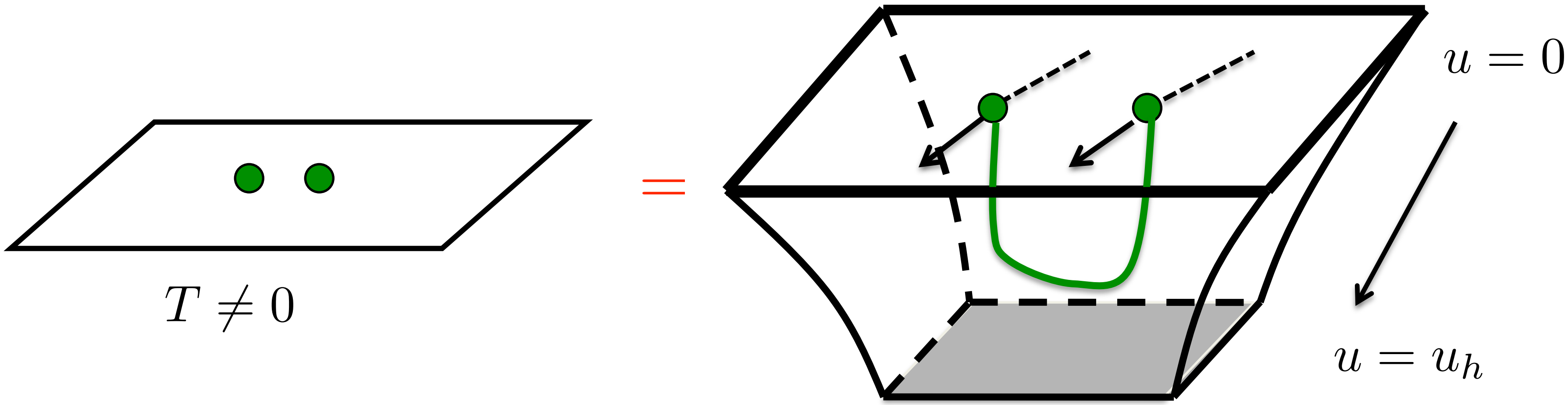
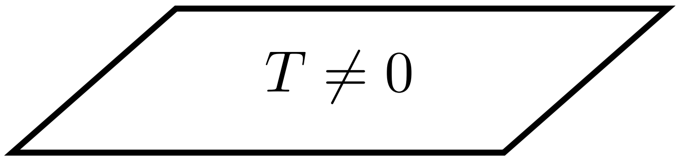


But we are interested in studying an anisotropic strongly coupled plasma

How can we do that using the AdS/CFT correspondence?

AdS/CFT toolkit

The gauge theory that we will consider is a deformation of $\mathcal{N} = 4$ SYM



$$S = S_{\mathcal{N}=4} + \int \theta(\vec{x}) \mathrm{Tr} F \wedge F$$

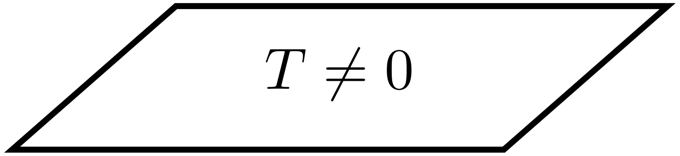
with $\theta(\vec{x}) = 2\pi n_{D7} z$

dimensions of energy

AdS/CFT toolkit

The gauge theory that we will consider is a deformation of $\mathcal{N}=4$ SYM.

The field dual to the θ-term is the axion



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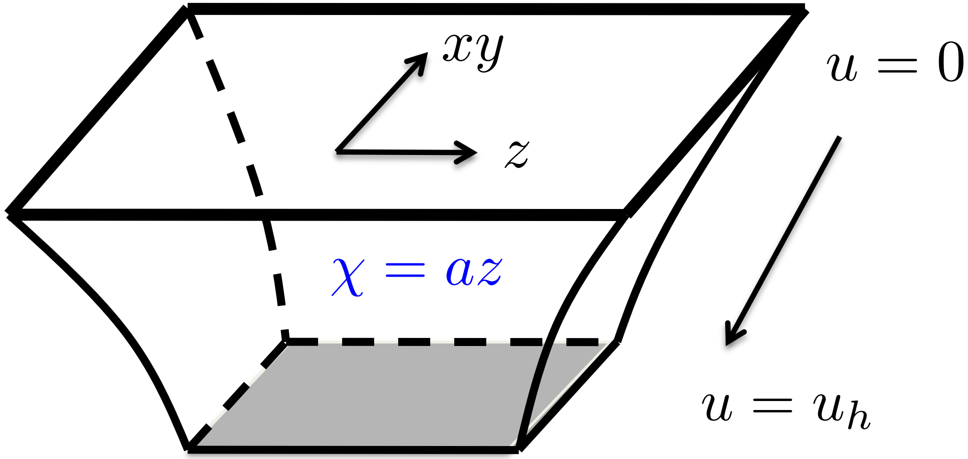

$$S = S_{\mathcal{N}=4} + \int \theta(\vec{x}) \mathrm{Tr} F \wedge F$$

with $\theta(\vec{x}) = 2\pi n_{D7} z$

$\longrightarrow$ $$\tau = \frac{\theta}{2\pi} + \frac{4\pi i}{g_{\mathrm{YM}}^2} = \chi + i e^{-\phi}$$

$\longrightarrow$ The axion is magnetically sourced by D7-branes

AdS/CFT toolkit

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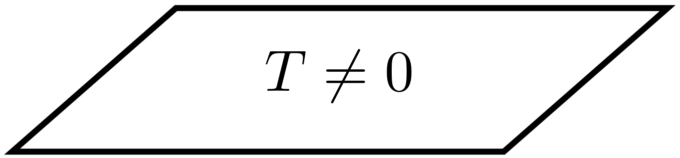

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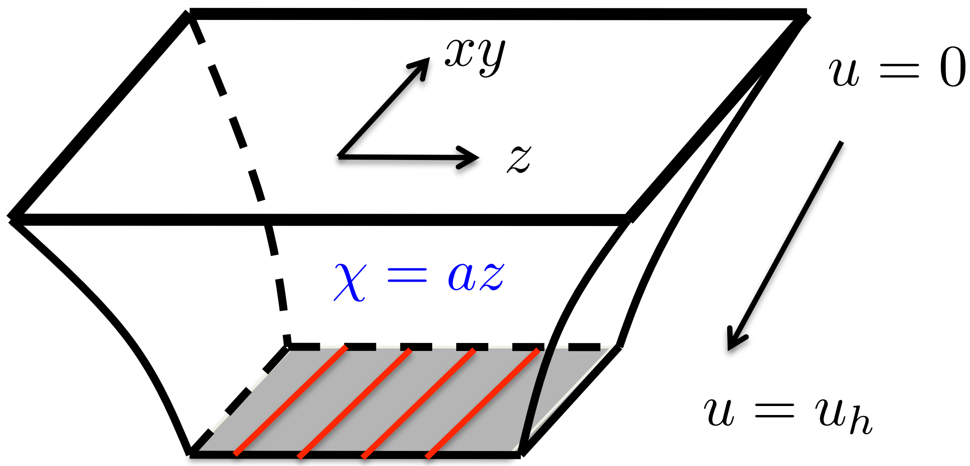

$$S = S_{\mathcal{N}=4} + \int \theta(\vec{x}) \mathrm{Tr} F \wedge F$$

with $\theta(\vec{x}) = 2\pi n_{D7} z$

	t	x	y	z	u	S^5
$N_c\ D_3$	x	x	x	x		
$n_{D_7}\ D_7$	x	x	x			x

AdS/CFT toolkit

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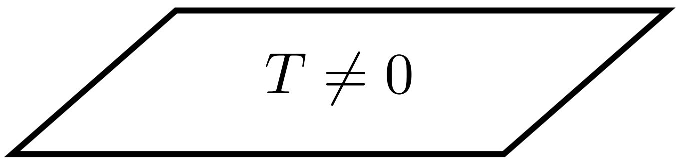

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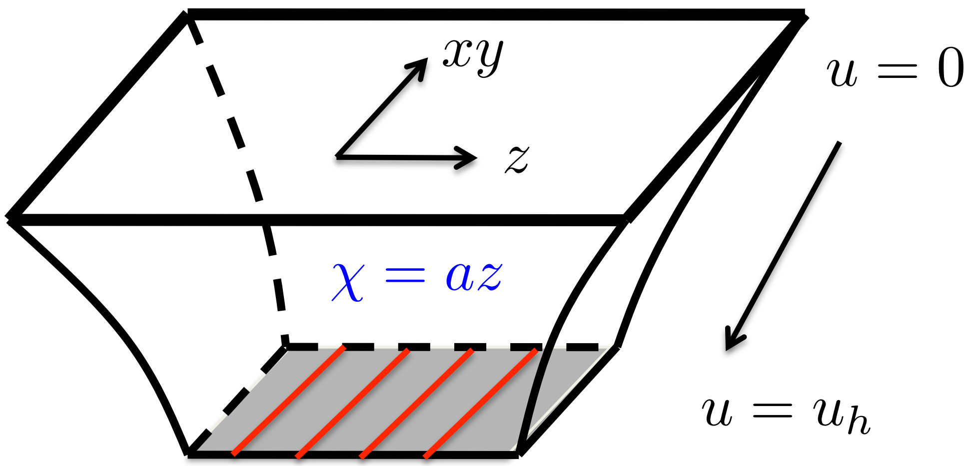

$$S = S_{\mathcal{N}=4} + \int \theta(\vec{x}) \mathrm{Tr} F \wedge F$$

with $\theta(\vec{x}) = 2\pi n_{D7} z$

and

$$a = \frac{\lambda n_{D7}}{4\pi N_c}$$

Density of D7-branes distributed along z

is a measure of the anisotropy

AdS/CFT toolkit

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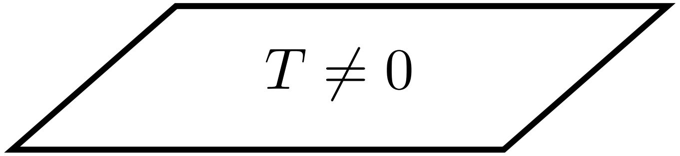

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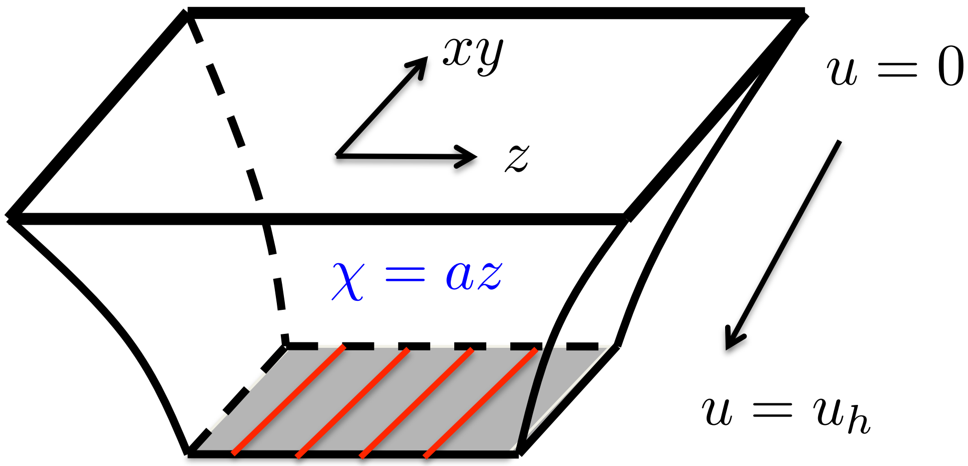


$$S = S_{\mathcal{N}=4} + \int \theta(\vec{x}) \mathrm{Tr} F \wedge F$$

with $\theta(\vec{x}) = 2\pi n_{D7} z$

Finally, putting all these ingredients together, and solving the eom...

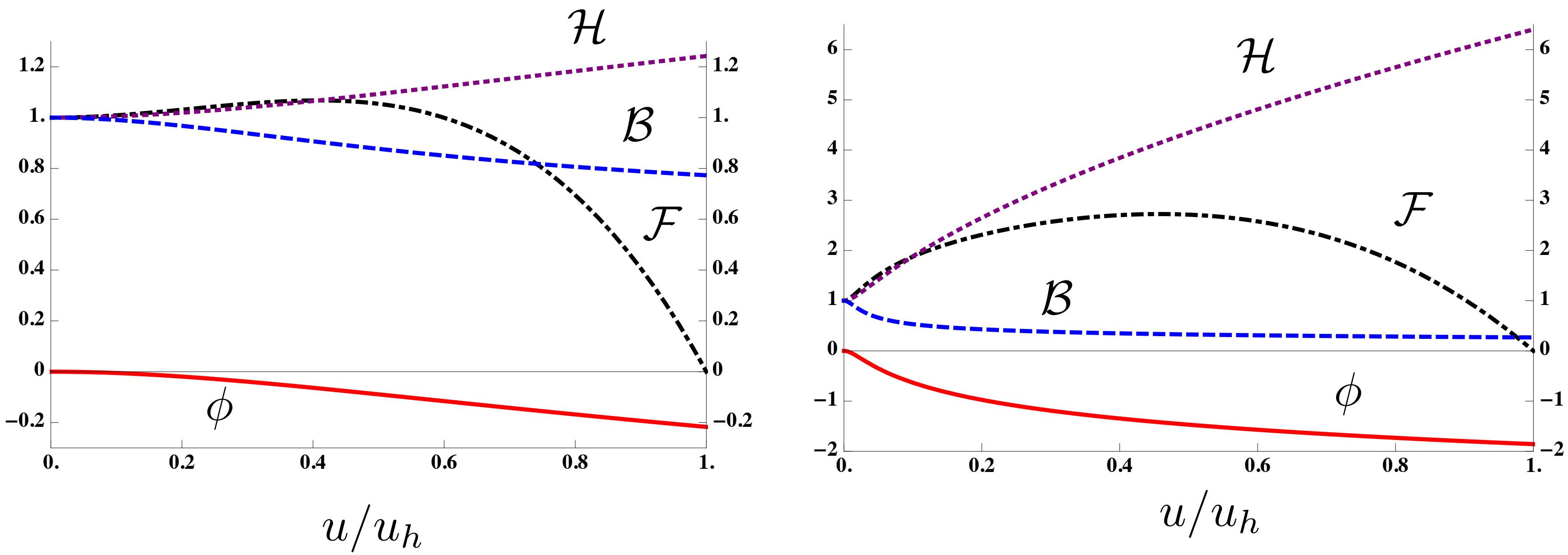
AdS/CFT toolkit

The anisotropic metric is

$$ds^2 = \frac{L^2}{u^2}\Big[-\mathcal{F}(u)\mathcal{B}(u)dt^2 + dx^2 + dy^2 + \mathcal{H}(u)dz^2 + \frac{du^2}{\mathcal{F}(u)}\Big]$$

$\chi(z) = az$ and $\phi \equiv \phi(u)$

[Mateos and Trancanelli]



AdS/CFT toolkit

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[Mateos and Trancanelli]

→ Regular on and outside the horizon

→ RG flow between AdS (UV) and Lifshitz type (IR)

→ The entropy density interpolates between

$$T \gg a \quad s \sim T^3 \qquad \text{and} \qquad T \ll a \quad s \sim a^{1/3}T^{8/3}$$

→ There is an analytical expression for the near-boundary behavior of metric functions $\mathcal{O}(u^6)$

Quarkonium physics

Preliminaries

→ The screening length L_s is define as the separation between a $q\bar{q}$ such that for $\ell < L_s$ $(\ell > L_s)$ it is energetically favorable for the pair to be bound (unbound).

Quarkonium physics

Preliminaries

- The screening length L_s is define as the separation between a $q\bar{q}$ such that for $\ell < L_s$ $(\ell > L_s)$ it is energetically favorable for the pair to be bound (unbound).

- We will determine L_s by comparing the action $S(\ell)$ of the $q\bar{q}$ pair to the action $S_{\rm unb}$ of the unbound system; i.e.

$$\Delta S(\ell) = S(\ell) - S_{\rm unb}$$

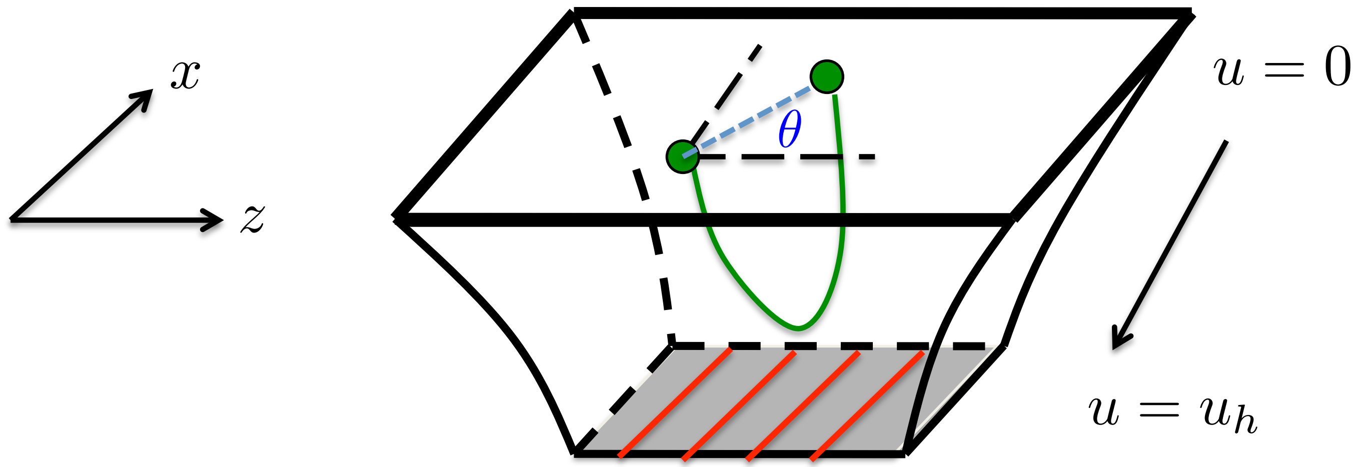
(In the Euclidean version, this criterion corresponds to determining which configuration has the lowest free energy)

The screening length is the maximum value of ℓ for which ΔS is positive

Quarkonium physics

1. Static case (to warm up)

Given the rotational symmetry in the xy-plane, the most general case is to consider the dipole in the xz-plane.



Choosing the static gauge $\tau = t$, $\sigma = u$, and the string embedding:

$$Z(u) = z(u)\cos\theta \quad \text{and} \quad X(u) = x(u)\sin\theta$$

Quarkonium physics

1. Static case

The action for the U-shaped string takes the form

$$S = -\frac{L^2}{2\pi\alpha'} 2 \int dt \int_0^{u_{\max}} du \frac{1}{u^2} \sqrt{\mathcal{B}(1 + \mathcal{F}\mathcal{H} \cos^2\theta z'^2 + \mathcal{F} \sin^2\theta x'^2)}$$

Quarkonium physics

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Two conserved momenta Π_z and Π_x associated to translation invariance in the x, z direction. Then, the on-shell action can be written as

$$S=-\frac{L^2}{2\pi\alpha'}2\int dt\int_0^{u_{\rm max}}du\frac{1}{u^2}\frac{\mathcal{B}\sqrt{\mathcal{F}\mathcal{H}}}{\sqrt{\mathcal{F}\mathcal{B}\mathcal{H}-u^4(\Pi_z^2+\mathcal{H}\Pi_x^2)}}$$

where the turning point $u_{\rm max}$ is determined from the condition

$$x'(u_{\rm max})=z'(u_{\rm max})\to\infty$$

Quarkonium physics

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which in terms of the momenta reads

$$\mathcal{F}\mathcal{B}\mathcal{H} - u^4(\Pi_z^2 + \mathcal{H}\Pi_x^2)|_{u_{\max}} = 0 \quad \Rightarrow \quad u_{\max} \equiv u_{\max}(a, T, \Pi_i)$$

Quarkonium physics

1. Static case

From the boundary conditions we obtain the relation between the momenta Π_z , Π_x and the quark-antiquark separation ℓ

$$\frac{l}{2} = \int_0^{u_{\max}} du X' = \int_0^{u_{\max}} du Z'$$

Quarkonium physics

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$$\frac{l}{2} = \int_0^{u_{\rm max}} du X' = \int_0^{u_{\rm max}} du Z'$$

Finally, to determine L_s , we need to subtract from the U-shaped string action, that of the unbound pair (i.e. two straight strings)

$$S_{\rm unb} = -\frac{L^2}{2\pi\alpha'} 2 \int dt \int_0^{u_{\rm h}} du \frac{\sqrt{\mathcal{B}}}{u^2}$$

The UV divergences associated to integrating all the way to the boundary cancel out in the difference, and there are no IR divergences.

Quarkonium physics

1. Static case

The isotropic result $a = 0$ ($H \to 0,\ B \to 1,\ F \to f$)

$L_s \simeq \frac{0.24}{T}$ [Rey et al; Brandhuber et al] or $L_s \simeq 0.24(\underbrace{\frac{\pi^2 N_c^2}{2s}}_{\text{at constant entropy density}})^{1/3}$

Quarkonium physics

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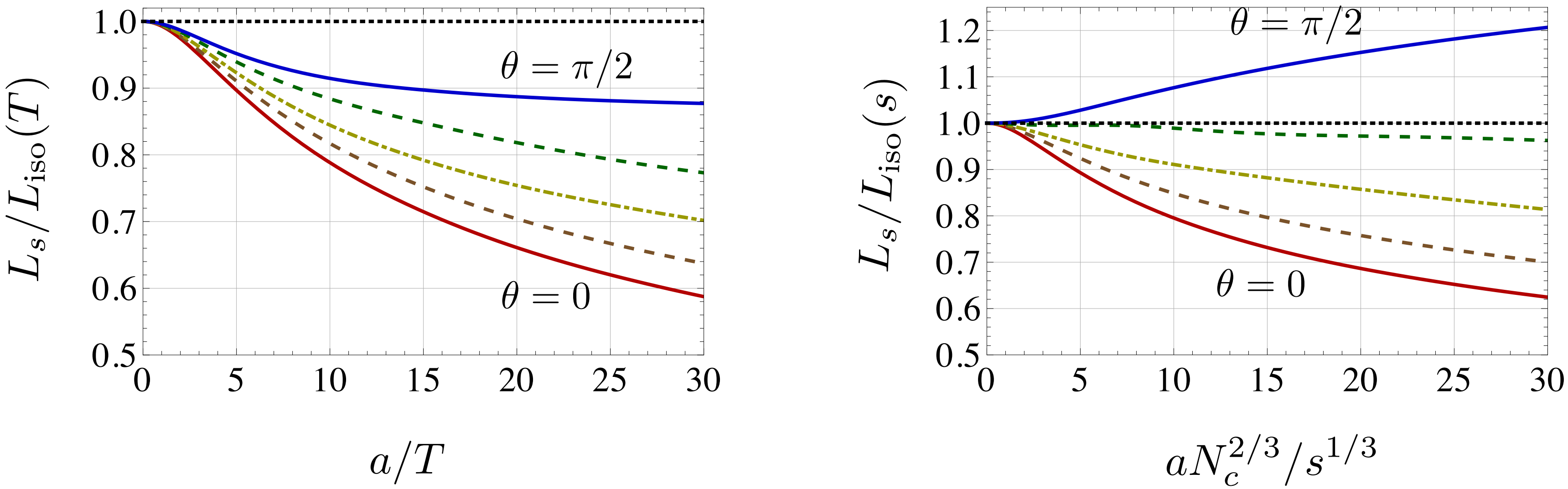
The anisotropic results:



Quarkonium physics

2. Dipole in a plasma wind

We will first consider the ultra-relativistic limit. There are at least two important reasons for doing so:

- It is relevant for the experiments.
- It can be understood analytically. For the isotropic case:

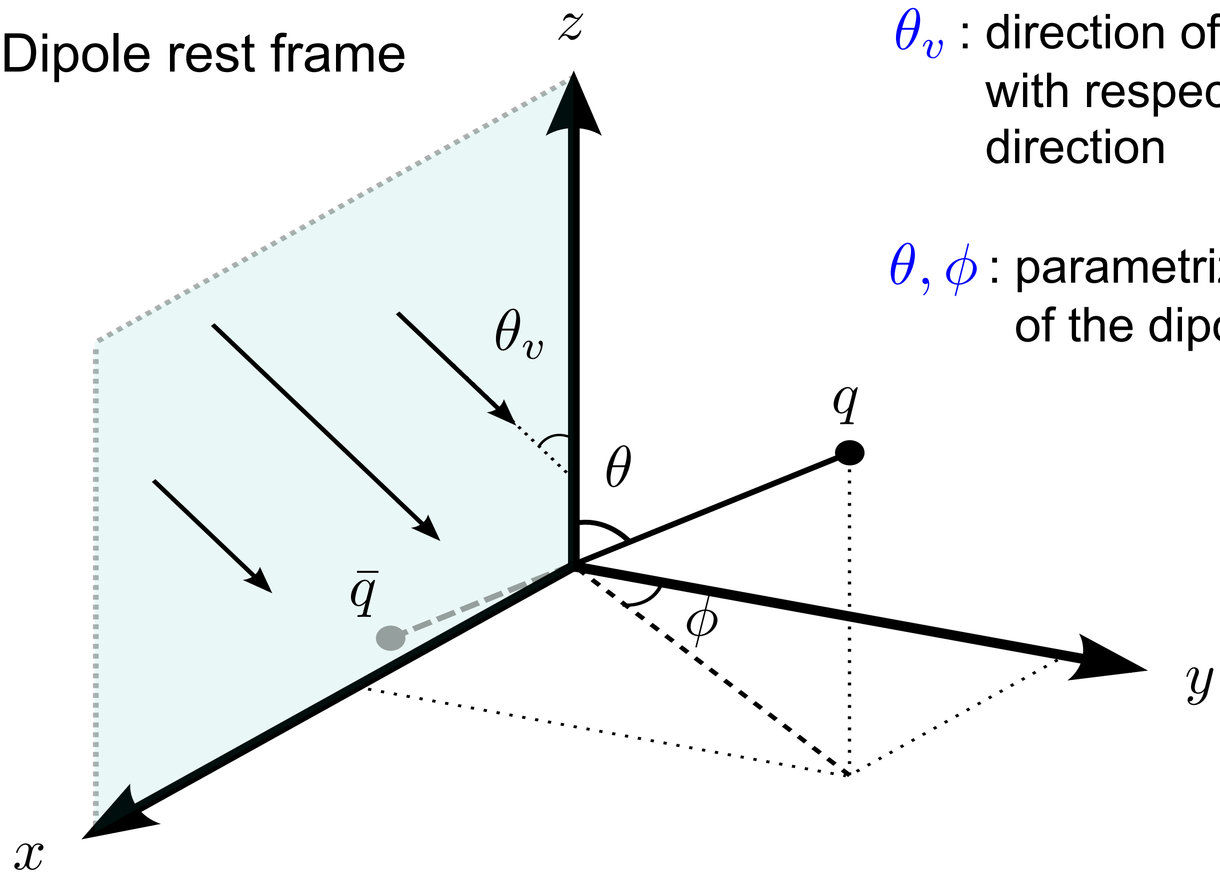
$$L_s(T,v) \sim (1-v^2)^{1/4}$$ [Liu et al.]

Quarkonium physics

2. Dipole in a plasma wind

Our set up:

→ Dipole rest frame



θ_v : direction of the wind (velocity) with respect to the anisotropic direction

θ, ϕ : parametrized the orientation of the dipole

Quarkonium physics

2. Dipole in a plasma wind

As in the static case, to determine the screening length we need to compare the actions of a bound and an unbound quark-antiquark pair.

Quarkonium physics

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As in the static case, to determine the screening length we need to compare the actions of a bound and an unbound quark-antiquark pair.

Let us summarize the important steps:

→ The unbound action is that of a string moving with constant velocity

[MCh, Fernandez, Mateos and Trancanelli]

Quarkonium physics

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[MCh, Fernandez, Mateos and Trancanelli]

→ The position of the turning point is now $u_{\max} \equiv u_{\max}(a, T, \Pi_i, v)$

It is easy to check that for a fixed separation of the string endpoints,

$$\lim_{v \to 1} u_{\max} \to 0$$

Then the dynamics of the string can be determined using the near boundary expansion of the metric.

Quarkonium physics

2. Dipole in a plasma wind

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$$\lim_{v \to 1} u_{\rm max} \to 0$$

→ The analytical expression for the near boundary metric

$$\mathcal{F}, \mathcal{B}, \mathcal{H} \sim 1 + \underbrace{W_i(a)}_{T\text{ - independent}} u^2 + G_i(a, T) u^4 + \mathcal{O}(u^6)$$

[Mateos et al.]

Quarkonium physics

2. Dipole in a plasma wind

We want to compare the two actions in the ultra-relativistic limit and see how they scale with $(1-v^2)$

Quarkonium physics

2. Dipole in a plasma wind

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After some algebra:

$$\Delta S(l, v) \sim (1 - v^2)^{-1/2} \times \underbrace{(\text{finite integral})}_{\mathcal{I}(a, \theta_v, \Pi_i, \mathcal{O}(u^6))}$$

motion outside the transverse plane

$\Rightarrow$ T independent!

$$\Delta S(l, v) \sim (1 - v^2)^{-1/4} \times \underbrace{(\text{finite integral})}_{\mathcal{I}(a, T, \theta_v, \Pi_i, \mathcal{O}(u^6))}$$

motion within the transverse plane

Quarkonium physics

2. Dipole in a plasma wind

We want to compare the two actions in the ultra-relativistic limit and see how they scale with $(1-v^2)$

After some algebra:

$$\Delta S(l,v) \sim (1-v^2)^{-1/2} \times (\text{finite integral})$$ motion outside the transverse plane

$$\Delta S(l,v) \sim (1-v^2)^{-1/4} \times (\text{finite integral})$$ motion within the transverse plane

And finally, using the boundary conditions, we obtain how the screening length scales in the ultra-relativistic limit:

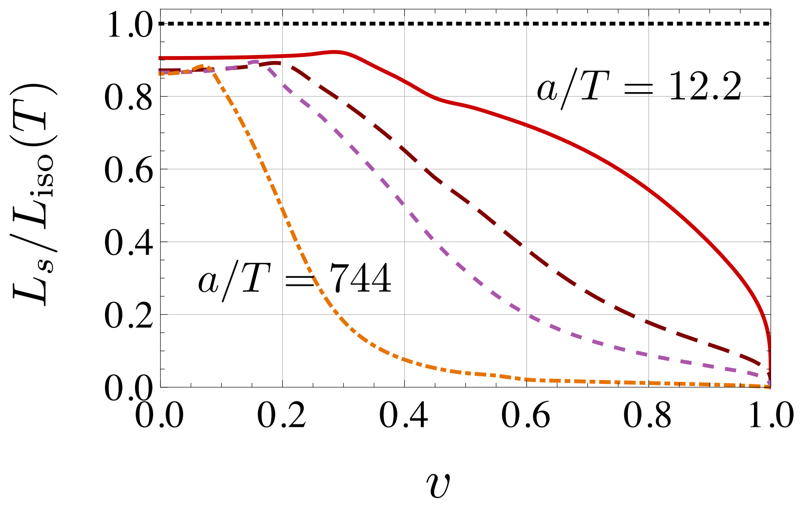
$$\boxed{L_s \sim \begin{cases} (1-v^2)^{1/2} \times \mathcal{I}(a, \Pi_i, \mathcal{O}(u^6)) \text{ if } \theta_v \neq \pi/2 \\ (1-v^2)^{1/4} \times \mathcal{J}(a, T, \Pi_i, \mathcal{O}(u^6)) \text{ if } \theta_v = \pi/2 \end{cases}}$$

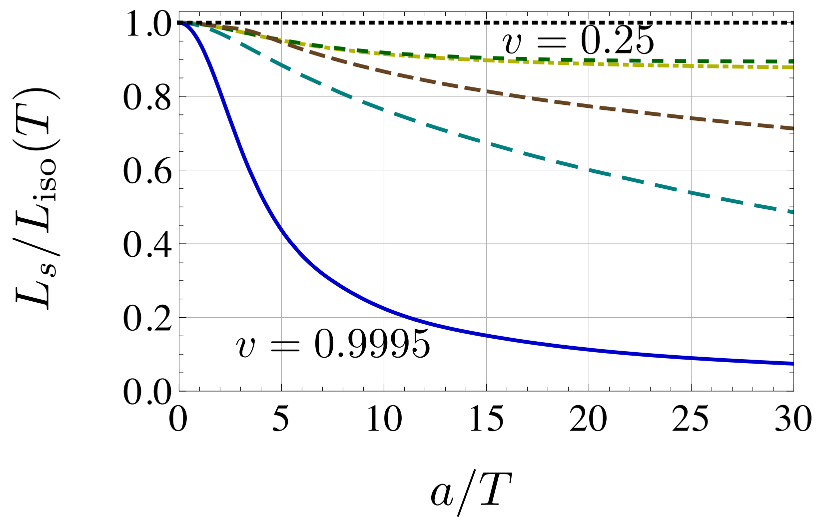
Quarkonium physics

2. Dipole in a plasma wind

A glimpse of the numerical results:

→ Wind along “z” and dipole along “x”





$L_s/L_{\rm iso}$ vanishes as $(1-v^2)^{1/4}$ in the limit $v \to 1$

Quarkonium physics

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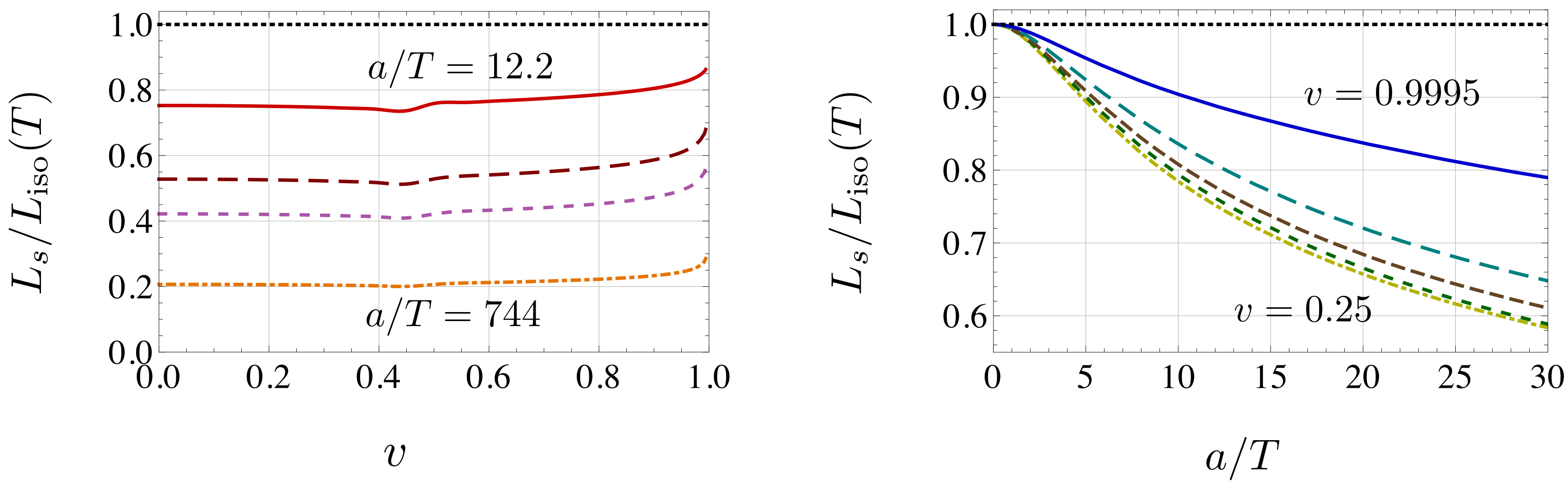

$L_s/L_{\rm iso}$ approaches a finite, non-zero value as $v \to 1$

Quarkonium physics

Another interesting limit to consider: $a/T \gg 1$

Quarkonium physics

Another interesting limit to consider: $a/T \gg 1$

Two observations:

→ The proper velocity along "z" of a point on the string at some u

$$v_{\text{proper}}(u) = v_z \sqrt{\frac{\mathcal{H}(u)}{\mathcal{F}(u)\mathcal{B}(u)}}$$

$\mathcal{H}(u)$ increases from $u = 0$ to $u = u_h$, more steeply as a/T increases, $\mathcal{F}(u)\mathcal{B}(u)$ has the opposite behavior.

$\Rightarrow$ Maximum value of $u_{\max}$ beyond which v_{proper} becomes superluminal

Quarkonium physics

Another interesting limit to consider: $a/T \gg 1$

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Maximum value of $u_{\rm max}$ beyond which $v_{\rm proper}$ becomes superluminal

→ We can show that for $v_z \neq 0$, $u_{\rm max}$ decreases as a/T increases. More over,

$$\lim_{a/T \gg 1} u_{\rm max} \to 0 \quad \Rightarrow$$

Use near boundary metric to study L_s

Quarkonium physics

Another interesting limit to consider: $a/T \gg 1$

→ It is straight forward to check that

For a fixed value of $v_z \neq 0 \quad \Rightarrow \quad L_s \sim a^{-1}$

T independent as in the ultra-relativistic case

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$$\boxed{\Rightarrow \quad T = 0 \text{ a meson will dissociate for sufficiently large anisotropy } a_{\mathrm{diss}}}$$

For motion within the transverse plane ($v_z = 0$) $\Rightarrow$ $L_s \sim f(a, T)$

$$\boxed{\text{No } a_{\mathrm{diss}} \text{ when } T \to 0}$$

Quarkonium physics

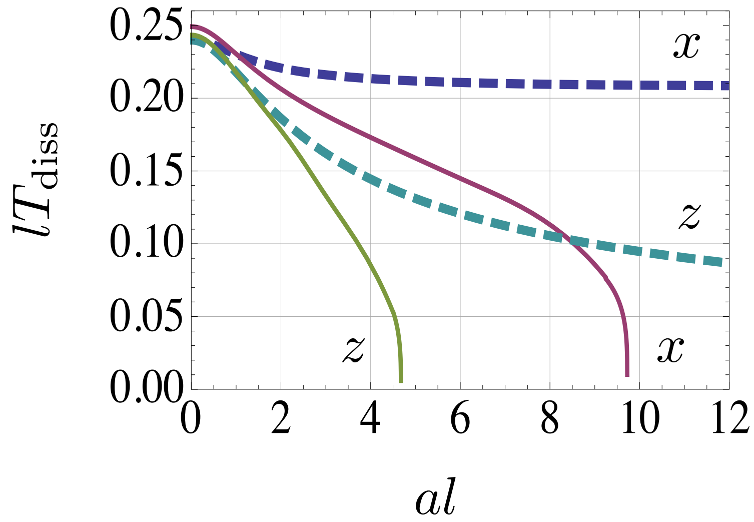
→ So far we have studied $L_s(a,T,v)$, but clearly we could also think of $T_{\rm diss}(a,\ell,v)$ and $a_{\rm diss}(T,\ell,v)$

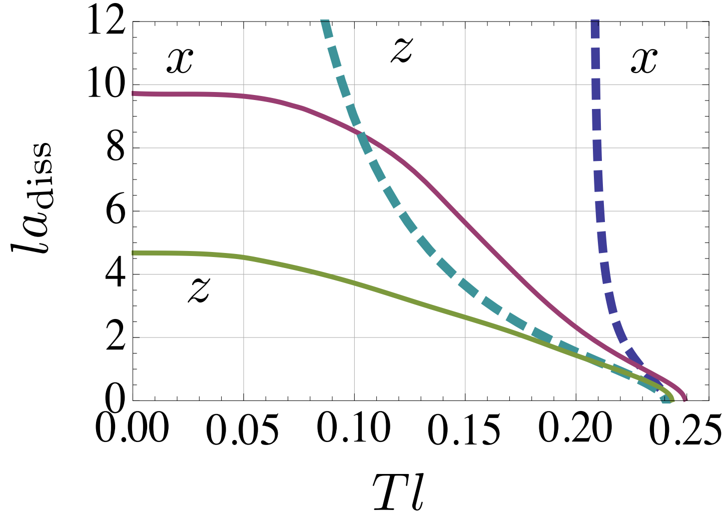
i.e. $T_{\rm diss}(a,\ell,v)$ characterizes the dissociation of a qq-pair of fixed size ℓ in a plasma with a given degree of anisotropy a. Analogously for $a_{\rm diss}$.

→ Using our results for the screening length, we can study the behavior of $T_{\rm diss}(a,\ell,v)$ and $a_{\rm diss}(T,\ell,v)$

Quarkonium physics

Numerical results: at rest; moving along the z-direction ($v = 0.45$)





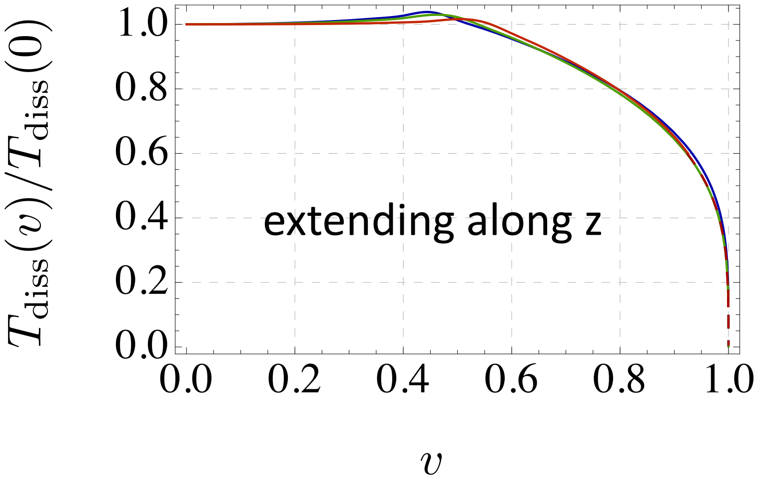
→ As explained before, even at zero temperature a meson of size ℓ will dissociate if the anisotropy is increased above

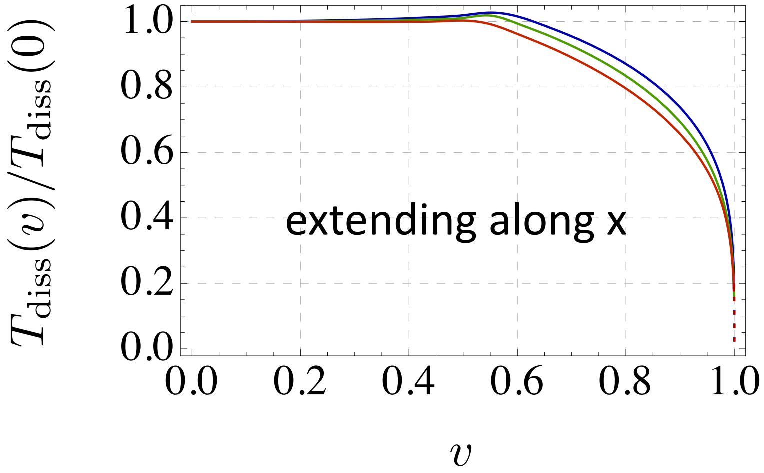
$$a_{\rm diss}(T = 0, \ell) \propto 1/\ell$$

and the proportionality constant is a decreasing function of the velocity

Quarkonium physics

Numerical results for motion within the transverse plane:





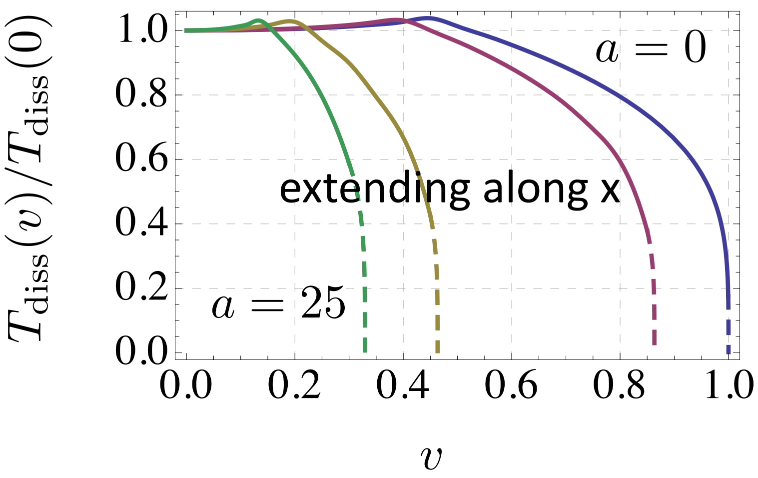
The behavior is qualitatively analogous to that of the isotropic case.

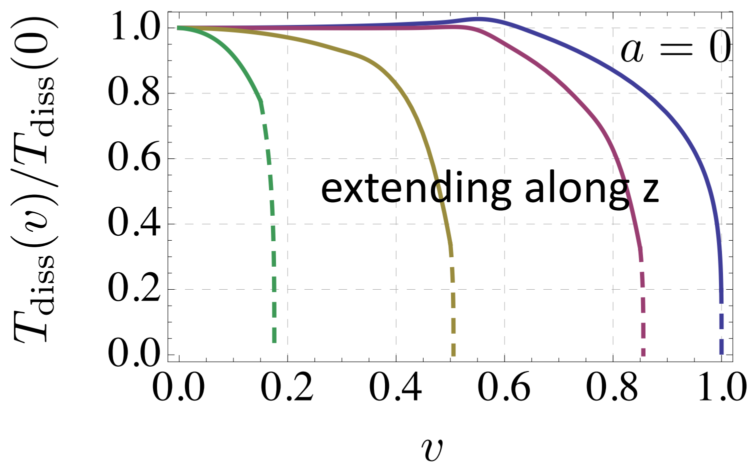
$$T_{\rm diss}(v) \simeq T_{\rm diss}(0)(1-v^2)^{1/4}$$

[Liu et al.]

Quarkonium physics

Numerical results for motion outside the transverse plane:

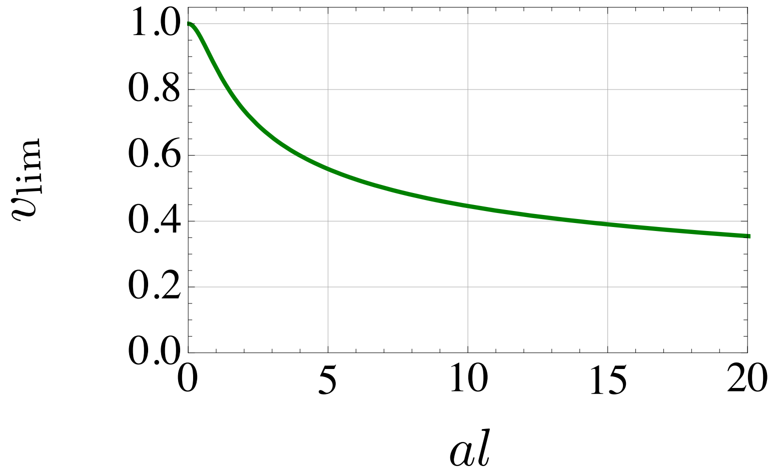




There is a limiting velocity $v_{\rm lim} < 1$ even at zero temperature!

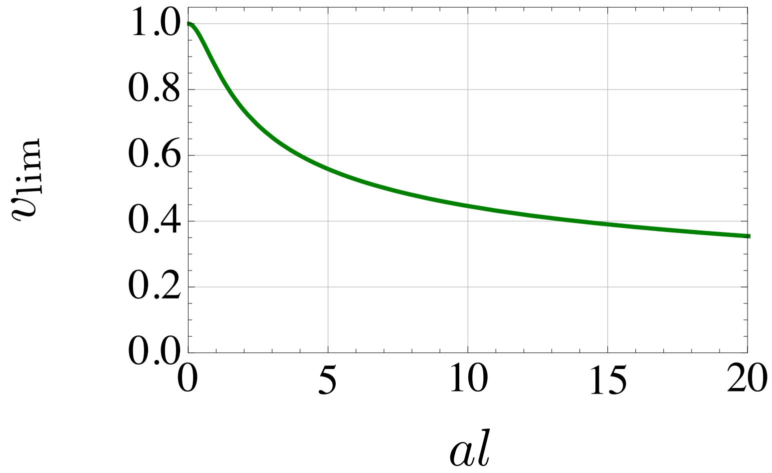
Quarkonium physics

Limiting velocity for a fixed anisotropy and $T = 0$, meson oriented along the x-direction and moving along the z-direction



Quarkonium physics

Limiting velocity for a fixed anisotropy and $T = 0$, meson oriented along the x-direction and moving along the z-direction



In the case of ultra-relativistic motion and $a/T \gg 1$:

$$a_{\rm diss} \sim \frac{1}{\ell}(1 - v_{\rm lim}^2)^{1/2} \ \text{if} \ \ \theta_v \neq \pi/2$$

$$T_{\rm diss} \sim \frac{1}{\ell}(1 - v_{\rm lim}^2)^{1/4} \ \text{if} \ \ \theta_v = \pi/2$$

Conclusions

- We have completely characterized the screening length for quarkonium mesons moving with arbitrary velocities and orientations.

- Mesons dissociate above certain critical value of the anisotropy, even at zero temperature.

- There is a limiting velocity for mesons moving through the plasma, even at zero temperature .

- The gravity calculation involves only the coupling of the string to the background metric, so any anisotropy that gives rise to a qualitatively similar metric will yield qualitatively similar results.

Back up slide

The near-boundary behavior of metric functions:

$$\begin{cases}\mathcal{F} = 1 + \dfrac{11}{24}a^2u^2 + \left(\mathcal{F}_4 + \dfrac{7}{12}a^4\log u\right)u^4 + O(u^6)\,, \\[2ex] \mathcal{B} = 1 - \dfrac{11}{24}a^2u^2 + \left(\mathcal{B}_4 - \dfrac{7}{12}a^4\log u\right)u^4 + O(u^6)\,, \\[2ex] \mathcal{H} = 1 + \dfrac{1}{4}a^2u^2 - \left(\dfrac{2}{7}\mathcal{B}_4 - \dfrac{5}{4032}a^4 - \dfrac{1}{6}a^4\log u\right)u^4 + O(u^6)\end{cases}$$

with $\mathcal{F}_4(a,T)$ and $\mathcal{B}_4(a,T)$