Condensed matter physics of heavy quarks

a third order phase transition at a finite baryon chemical potential

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T. Faulkner, HL, arXiv:0807.0063, and to appear

Heavy Quarkonia

$$m_H >> \Lambda_{QCD}, \;\; \alpha_S(m_H) < 1, \;\; d \sim (m_H \alpha_S(d))^{-1} << \Lambda_{QCD}^{-1}$$

Charm:

$$m_c \approx 1.3\,\mathrm{GeV}, \quad \alpha_S(m_c) \approx 0.3, \quad d \approx 0.5\,\mathrm{fm}$$

The radii of charmonium (J/ψ, ψ′, ...) and bottomonium (ϒ, ϒ’, ...) families provide a unique set of decreasing length scales in QCD.

Due to their small sizes, heavy quakonia like J/ψ could survive the deconfinement transition.

Good probes of the QGP

Quarkonia in a QGP

1. The potential between the quark and anti-quark in the bound state is weakened by the color screening of the plasma.

⇨ shallower bound state or no bound state at all

2. The bound state can be broken apart by collisions with gluons and quarks in the plasma.

⇨ medium-induced width

A quarkonium will dissociate at a sufficiently high temperature:

dissociation temperature T_d

Basic theoretical issues

- Color screening in a medium can be characterized by :

  L_S (T): screening length (decreases with T)

- Dissociation temperature T_d

  $d \sim L_S(T_d)$ d: size of a meson

- Ultimately:

$$\omega(k) - \frac{i}{2}\Gamma(k)$$

Important for understanding the strongly coupled QCD QGP

Needed for interpretation data from heavy ion collisions

Very difficult even in weakly coupled theories.

Lattice:

Screening length: well understood for quarks at rest,
not possible for moving quarks

some progress toward:

$$\omega(0) = M(T),\ \Gamma(0)$$

$\omega(k), \Gamma(k)$ not possible **(more interesting question)**

Some insights from AdS/CFT

Velocity enhanced screening

HL,Rajagopal,Wiedemann

Peeters, Sonnenschein, Zamaklar, Chernicoff, Garcia, Guijosa;

Color screening in a medium can be characterized by :

L_S (T): screening length (decreases with T)

At finite velocity ($\mathcal{N}$=4 SYM at strong coupling)

$$L_S(\mathrm{v}) \approx L_S(0)(1-\mathrm{v}^2)^{1/4} \sim (1-\mathrm{v}^2)^{1/4}\frac{1}{T}$$

$$\Rightarrow \quad T_d(\mathrm{v}) \sim (1-\mathrm{v}^2)^{1/4} T_d(0)$$

Important for J/ψ suppression in heavy ion collisions
Testable

Propagation of quarkonia in QGP

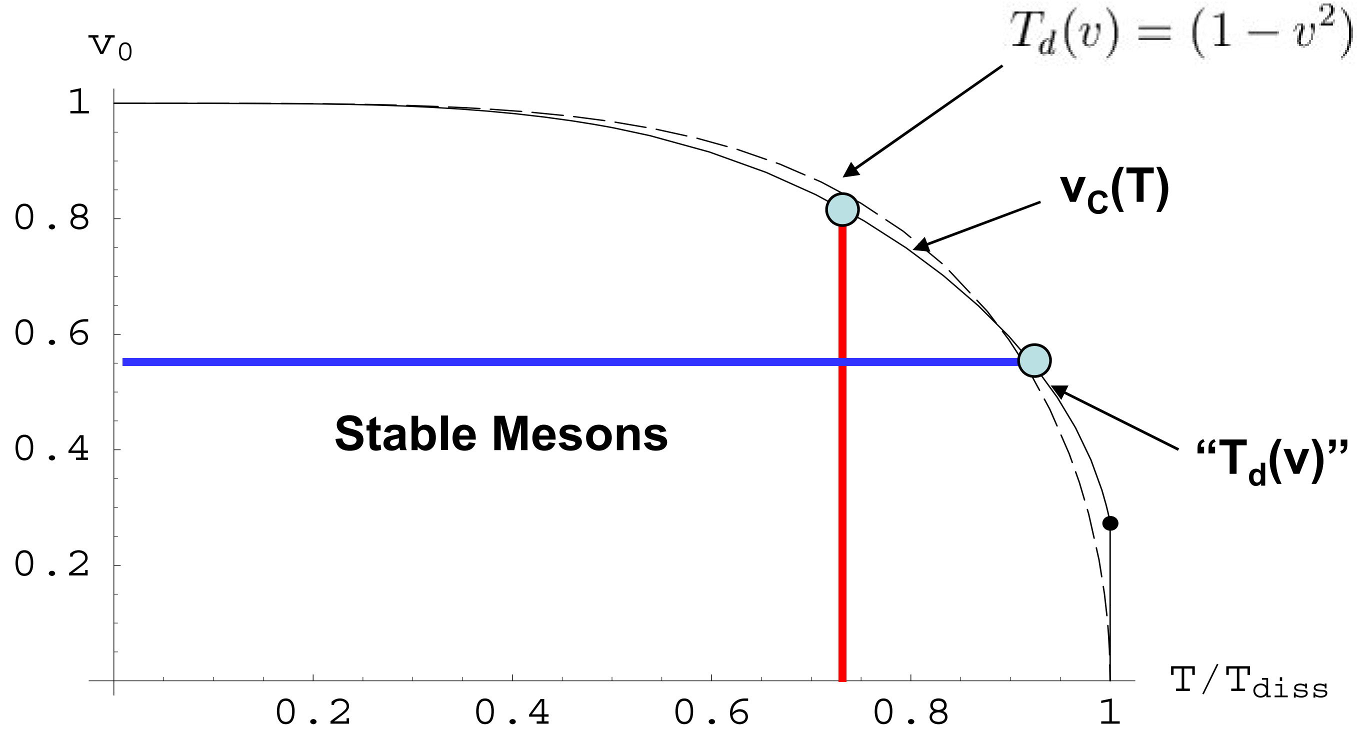
Speed limit :

$$\omega = v_C k, \; k \to \infty \qquad v_C < 1$$

Mateos, Myers and Thomson

Ejaz, Faulkner, HL, Rajagopal, Wiedemann

$$T_d(v) = (1 - v^2)^{\frac{1}{4}} T_d(0)$$



As v > v_C(T), quark and anti-quark get completely screened.

Purpose of this talk:

- What AdS/CFT can say about: $\Gamma(k)$

  for a strongly coupled QGP.

  Worldsheet instantons play an important role

- Phase structure for a strongly coupled SUSY gauge theory with flavor

  A third order phase transition driven by instantons

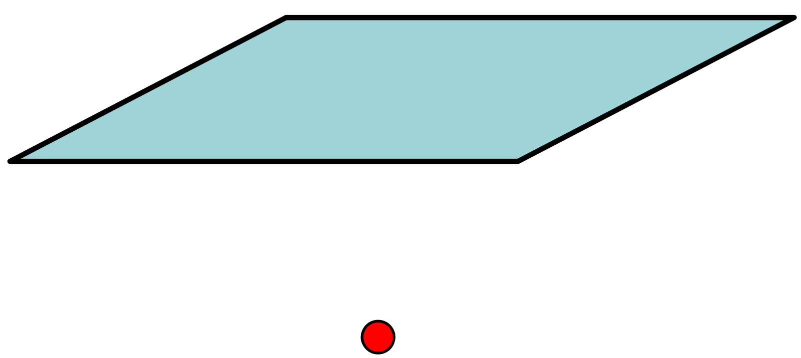
Adding flavors in AdS/CFT

Aharony, Fayyazuddin, Maldacena, Karch,Katz

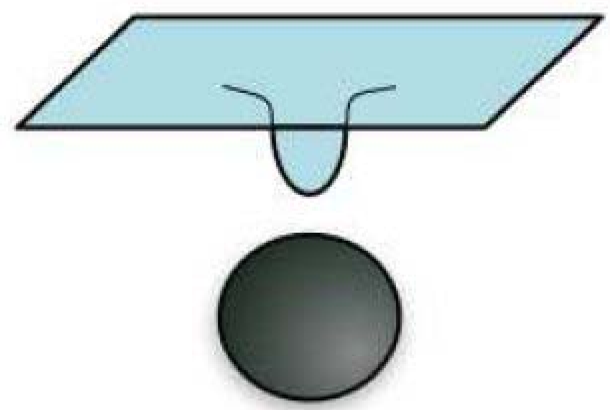
$\mathcal{N}$=4 SYM theory does not contain dynamical quarks.

Add N_F hypermultiplets in fundamental representation to $\mathcal{N}$=4 SYM → $\mathcal{N}$=2 theory with flavors

On gravity side, this can be achieved by adding N_F D7-branes to the $AdS_5 \times S^5$ geometry.



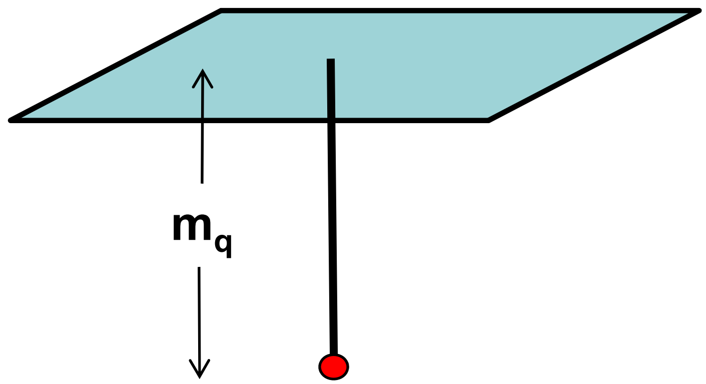
Zero temperature

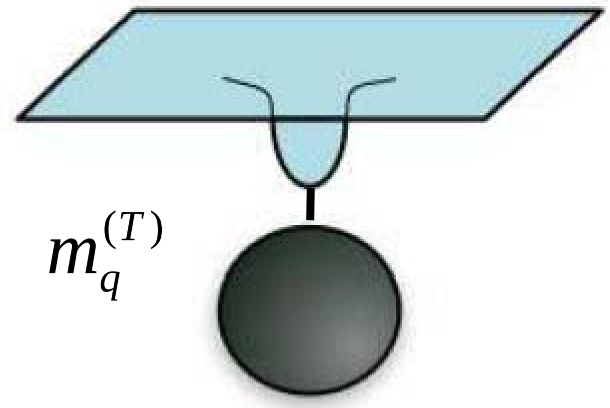


small T/m_q

Dictionary

Quarks:





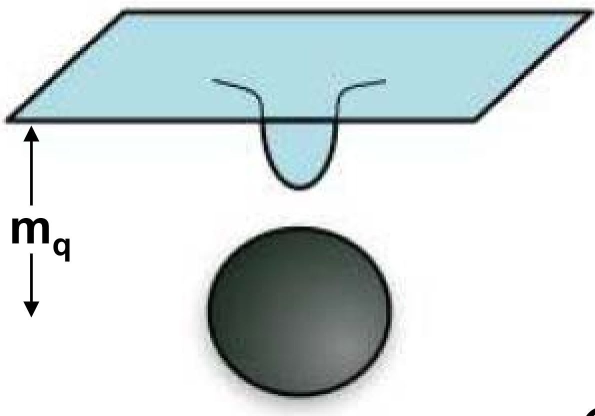
$$m_q^{(T)}(T) < m_q$$

Mesons: Open strings on D7 branes

Conserved baryon current : U(1) vector field of D7-branes

Baryon chemical potential $A_0(\infty) = \mu_q$

Meson Spectrum



Low lying meson spectrum can be found by solving linearized Laplace equations for small fluctuations on the D7-brane.

One finds a discrete spectrum of mesons:

Bare quark mass: m_q , Meson masses: $M \sim \frac{m_q}{\sqrt{\lambda}}$

Babington, Erdmenger, Evans, Guralnik, Kirsch;
Kruczenski, Mateos, Myers, Winters;

λ: 't Hooft coupling

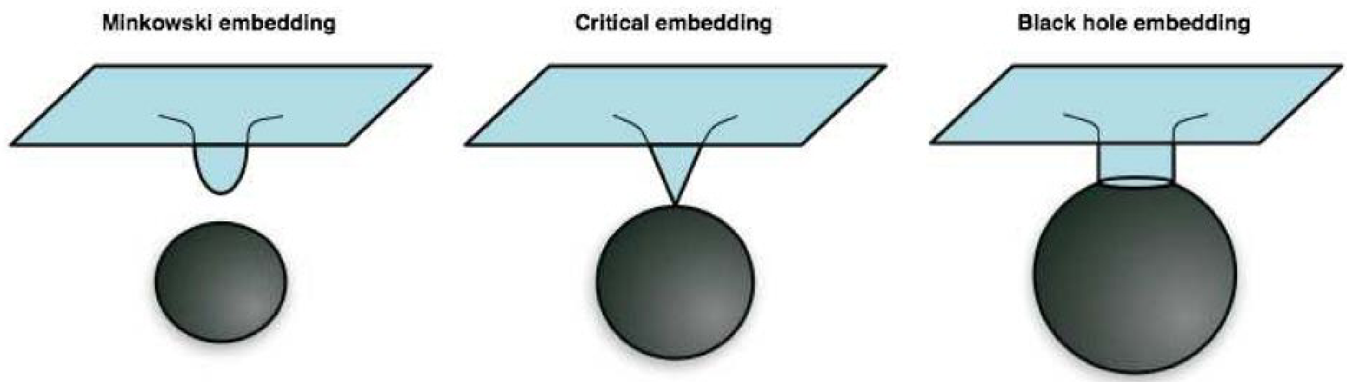
Very tightly bound: $E_{BE} \approx 2m_q^{(T)}$

Meson “Dissociation”

Babington, Erdmenger, Evans, Guralnik, Kirsch

Mateos, Myers and Thomson, Hoyos, Landsteiner, Montero

Meson dissociation:

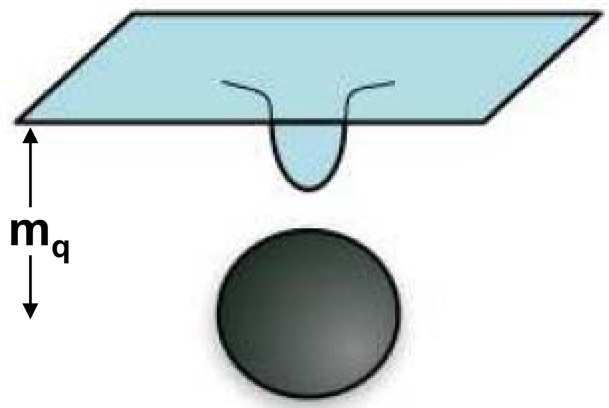


$$T_d \sim M \sim \frac{m_q}{\sqrt{\lambda}}$$

We will focus on: $T < T_d$

$$\Rightarrow \quad m_q^{(T)} \sim \sqrt{\lambda}\, T$$

Width of mesons?



Gravity approximation:

Mesons are stable for $T < T_d$, no width

completely disappear for $T > T_d$

Open strings on D7-brane sees a geometry which is smoothly capped off.

In fact mesons are stable to all orders in perturbative **α'** expansion.

However, bound states should always have a nonzero width in a finite temperature medium.

Field theory considerations

On the field theory side, meson widths receive contributions from:

- Mesons -> glue balls , lighter mesons, or other gauge singlets

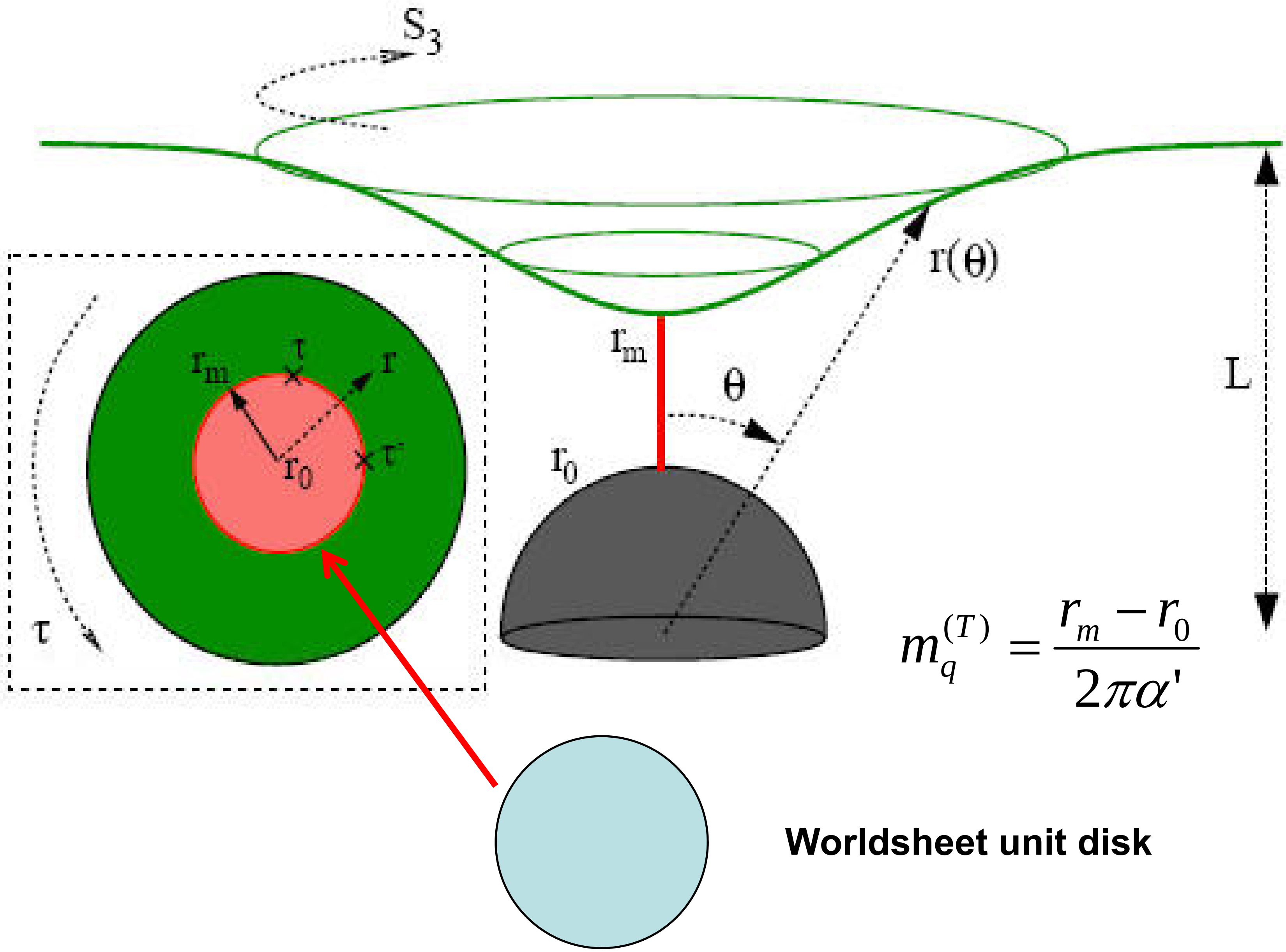
  (1/N_c suppressed, present at zero temperature)

- Breakup by high energy gluons:
- Breakup by thermal medium quarks

} **Medium effects**

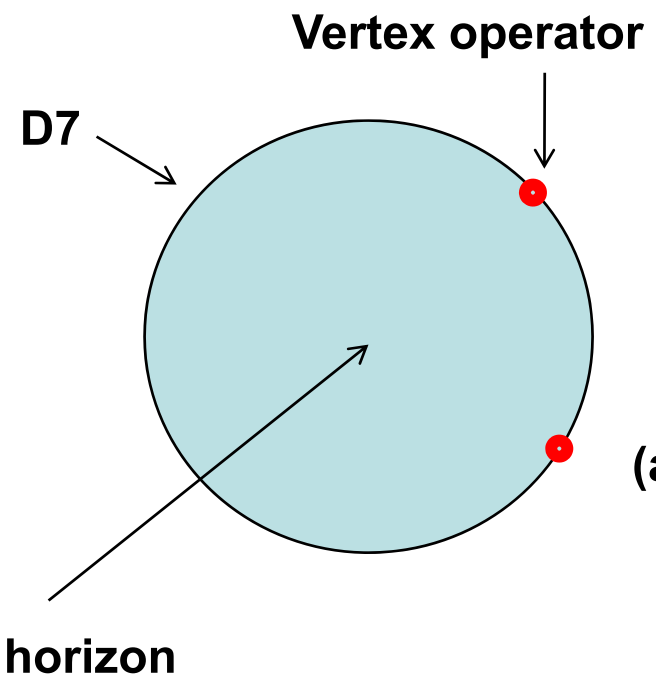
O(1) in N_C , non-perturbative in **α'**

Worldsheet instantons



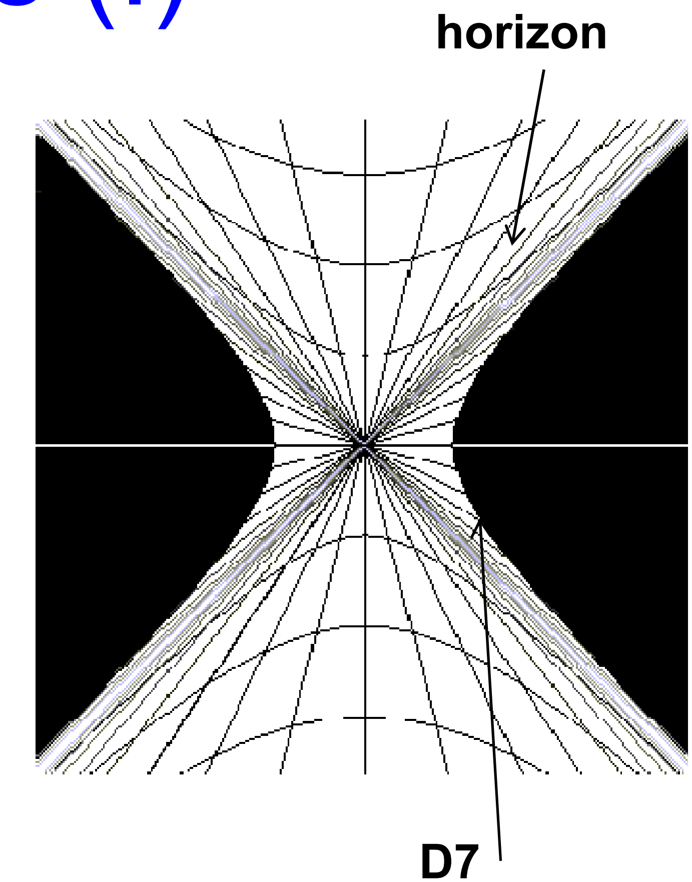
$$m_q^{(T)} = \frac{r_m - r_0}{2\pi\alpha'}$$

Meson widths (I)



Worldsheet instanton disk

(analytic continuation)



Rindler worldsheet

two-point function in Rindler spacetime

Meson widths (II)

Faulkner, HL

$$\Gamma_n^{(\pm 1)} = \frac{32\pi^3\sqrt{\lambda}}{N_c m_q^2} |\psi_n(\theta = 0)|^2 \, n_\pm$$

$$\frac{\Gamma_n(k)}{\Gamma_n(0)} = \frac{|\psi_n(\theta = 0; \vec{k})|^2}{|\psi_n(\theta = 0; \vec{k} = 0)|^2}$$

$$\frac{\Gamma(k)}{\Gamma(0)} \sim \frac{T^4 k^2}{M^6}, \qquad k \gg \frac{M^3}{T^2}$$