Gauge/Gravity Duality and QCD observables

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Outline

1. AdS/CFT and its application to QCD
   - Review of AdS/CFT
   - Application to study the strong interaction (QCD)
   - Modifications of the AdS/CFT duality:
     i) deformed AdS spaces + ii) introduction of flavours

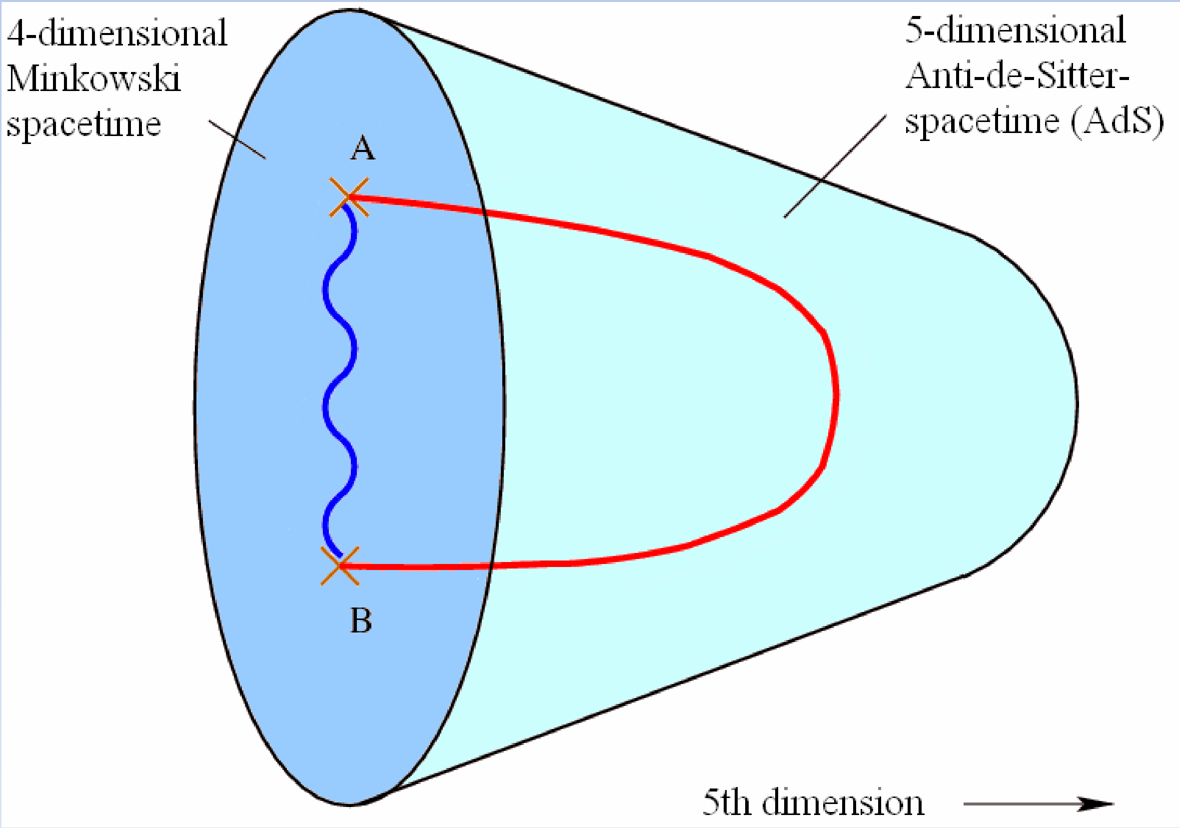
2. Observables
   - Example I: QCD at zero temperature (large N)
     U(1) spontaneous chiral symmetry breaking
   - Example II: QCD at finite temperature (large N)
     first-order phase transition
     meson melting in QGP

3. Conclusions

AdS/CFT correspondence

Equivalence (or duality) of two theories:

4D conformal field theory (CFT) ⇔ **5D theory of gravity** (string theory)
on AdS_5 (=anti-de-Sitter space, $\Lambda<0$)



Standard AdS/CFT duality

Standard AdS/CFT correspondence: Maldacena (1997)

i) boundary CFT: 4d *SU(N)* N=4 super Yang-Mills theory
ii) bulk: type IIB supergravity (string th.) on AdS_5 (x S^5)

supergravity approximation valid if $\lambda = 4\pi g_s N \gg 1$

Properties of the N=4 field theory:

1. *N>>1* (large)
2. supersymmetric
3. conformal invariance
4. all fields in the adjoint representation (only „gluons")

QCD:

1. *N=3*
2. not supersymmetric
3. no conformal invariance
4. gluons and quarks

Can we use AdS/CFT as dual theory of QCD?

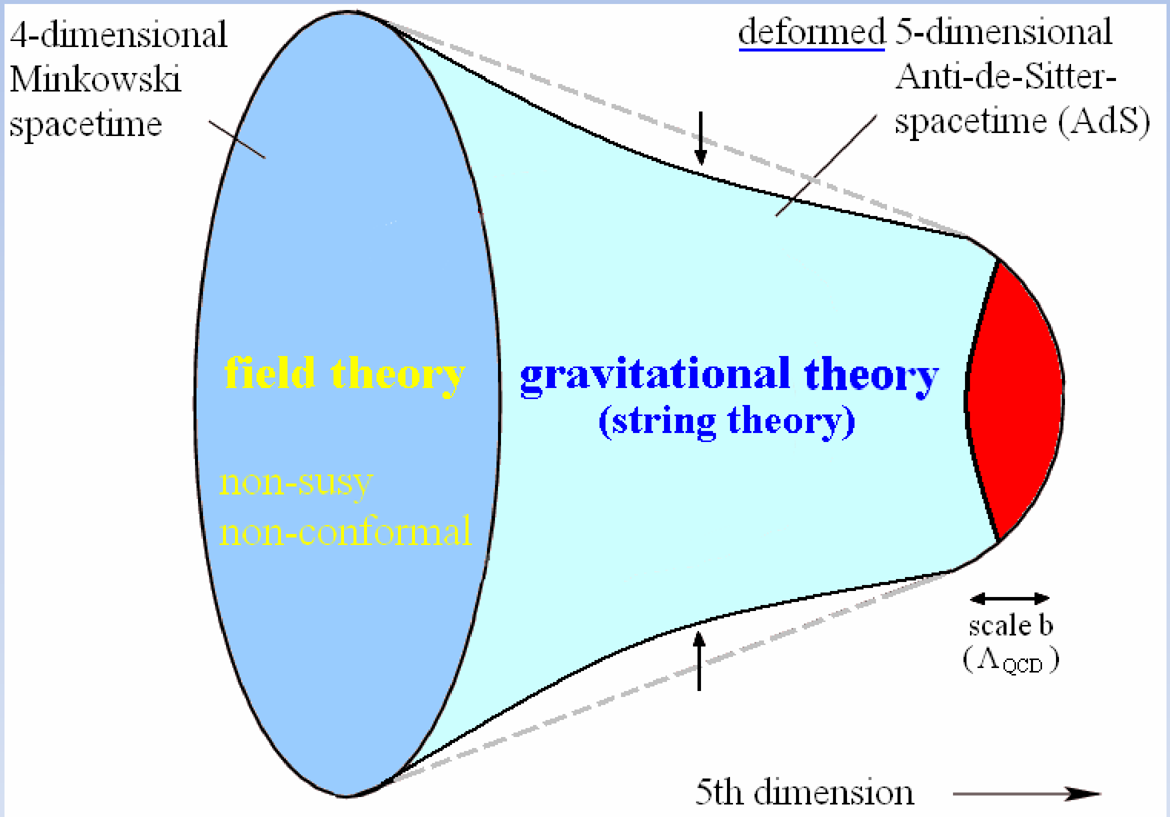
➡ **modify AdS/CFT**

Modifications of AdS/CFT

...to find a dual to a ``QCD-like" theory

First modification

deformation of the AdS background:



some examples:

Constable-Myers background

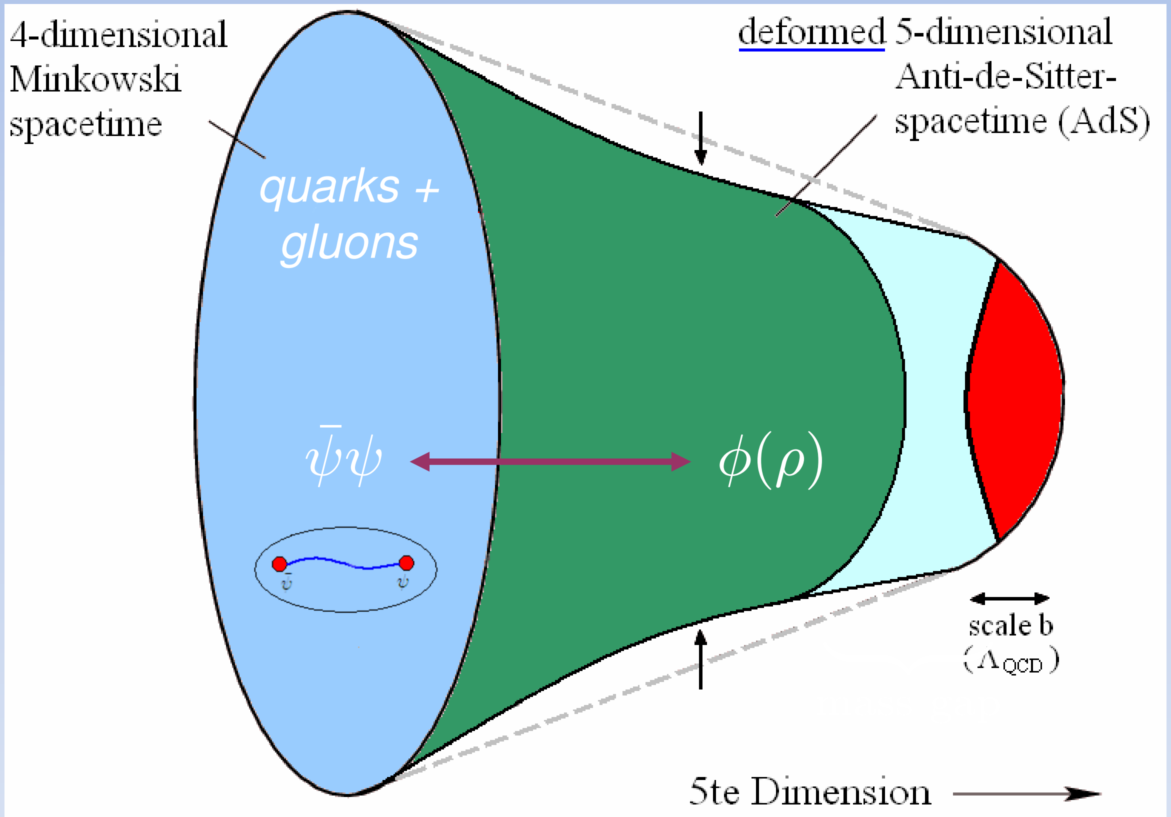
Gubser Dilaton-Flow

Maldacena-Nunez, Klebanov-Strassler, etc.

➡ breaking of supersymmetry and conformal invariance, bound states arise („confinement“)

Second modification

Introduction of fundamental fields („quarks“) in the duality:



Karch, Katz (2002)

Kruczenski, Mateos, Myers, Winters (2003)

Babington, Erdmenger, Evans, Guralnik, I.K. (2003)

probe (quenched) limit: $N_f \ll N_c$

➡ additional scalar or vector fields in the AdS-space which are dual to meson operators

Generalized AdS/CFT dictionary

Fundamental degrees of freedom added (``quarks")

$$\mathcal{O} \propto \bar{\psi}\psi,\ \bar{\psi}\gamma^\mu\psi \quad \overset{\text{dual to}}{\longleftrightarrow} \quad \phi(\rho, x^\mu),\ A^\mu(\rho, x^\mu)$$

mesons fluctuations

e.o.m of ϕ:

$$m^2 = -3 \Rightarrow \Delta = 3\,, \qquad m^2 = \Delta(\Delta - 4)$$

UV asymptotic behaviour of solutions to equation of motion:

$$\phi \propto m_q e^{-\rho} + c e^{-3\rho}$$

m_q = quark mass (source of $\mathcal{O}$)
c = quark condensate (vev of $\mathcal{O}$)

find regular solutions => $c(m_q)$

QCD observables

Example I: U(1) chiral symmetry breaking

Example I: U(1) chiral symmetry breaking

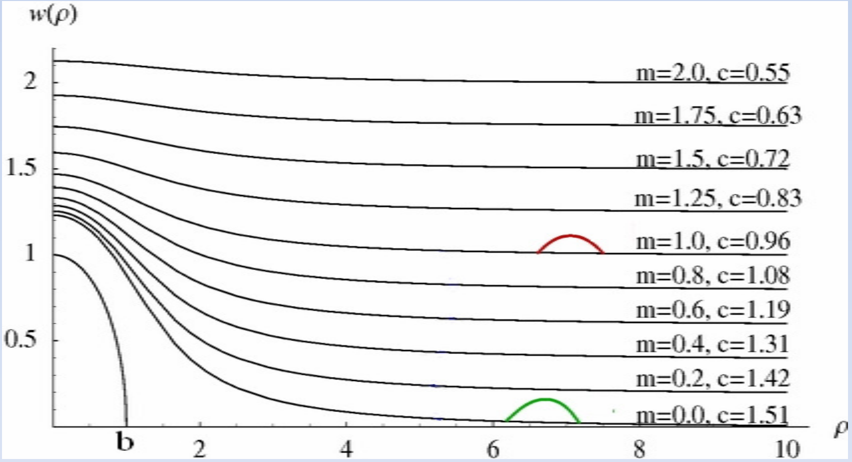
Babington, Erdmenger, Evans, Guralnik, I.K. (2003)

duality: i) branes in **Constable-Myers** background (confining)
ii) „QCD-like" SU(N) YM theory with N>>1 (T=0)

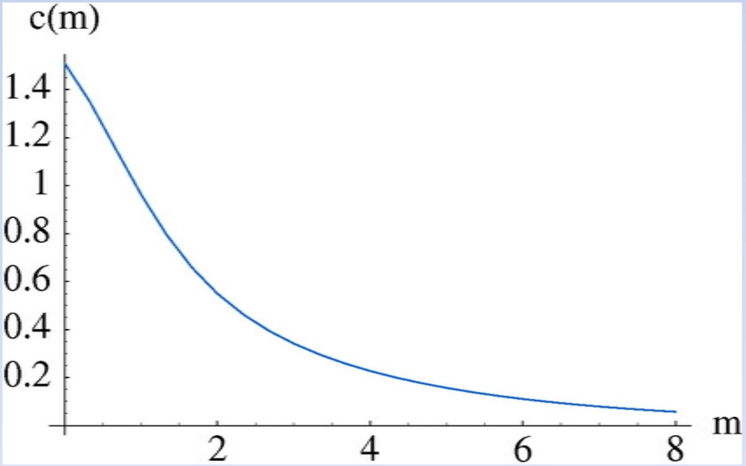
$U(1)_A$ spontaneous chiral symmetry breaking:

- $\psi \to e^{-i\varepsilon}\psi,\ \tilde{\psi} \to e^{-i\varepsilon}\tilde{\psi}$
- broken by quark condensate: $c = -\langle \psi\tilde{\psi} \rangle \neq 0$

embedding profiles + condensate:



„screening" effect



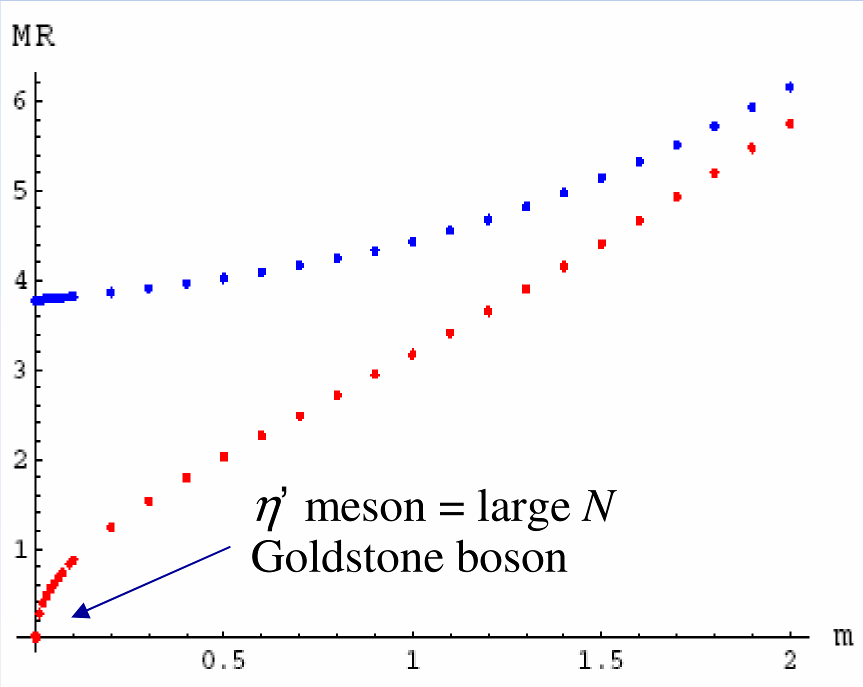
spont. U(1) breaking: $m \to 0$, $c \neq 0$

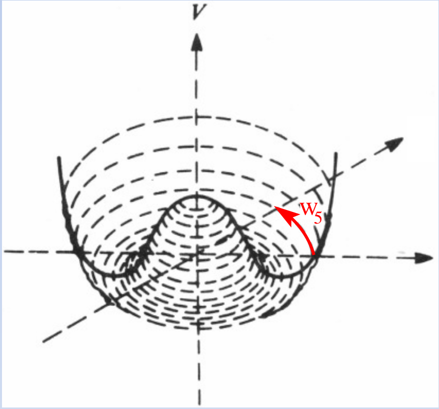
Meson spectrum and "large *N*" Goldstone boson (η')

Consider plane-wave-fluctutations $\delta\phi = f(\rho)\,\sin(k\,x)$ $(M^2 = -k^2)$ around the embedding profile $w = w(\rho)$

$\Rightarrow$ meson spectrum $M(m)$

GMOR at small m: $M \sim \sqrt{m_q}$



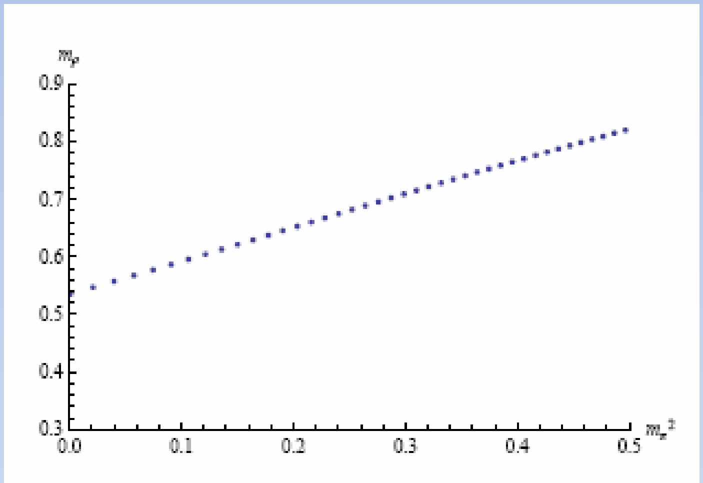


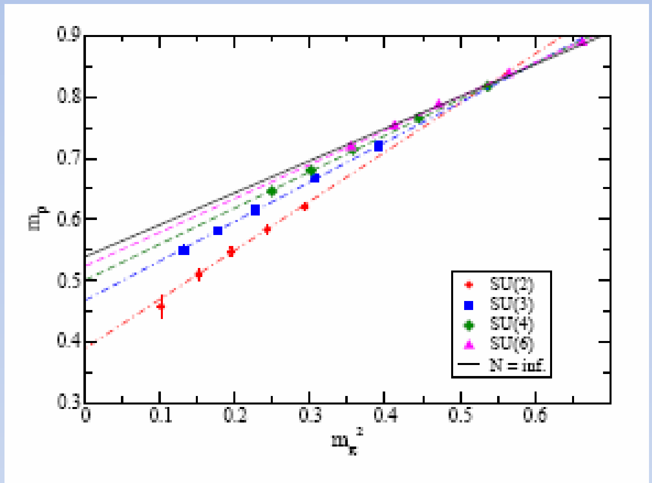
Goldstone boson due to spont. U(1) chiral SB

(anomaly suppressed at large N_c)

Comparison to lattice gauge theory

Mass of ρ–meson as function of π meson mass² (large N_c)





AdS/CFT: Erdmenger, Evans, Kirsch, Threlfall `07, review EPJA

$$\frac{m_\rho(m_\pi)}{m_\rho(0)} = 1 + 0.307 \left(\frac{m_\pi}{m_\rho}\right)^2$$

Lattice: Del Debbio, Lucini, Patella, Pica `07: slope 0.2816(2)

Bali, Bursa `08: slope 0.304(3)

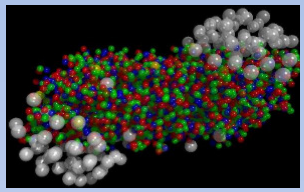
extrapolation (continuum limit):
slope 0.341 $\pm$0.023

QCD observables

Example II: First-order phase transition in QGP

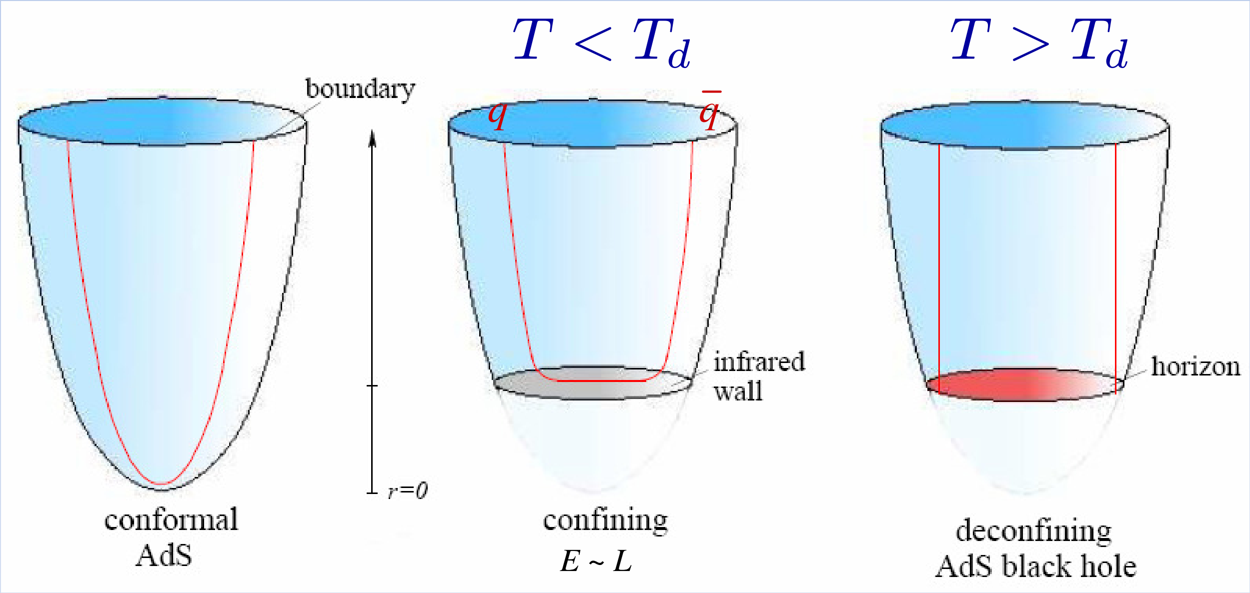
Example II: Finite Temperature

Quark gluon plasma: strongly-coupled state of matter above deconfinement temperature T_d



RHIC

Confinement/Deconfinement



AdS black hole: - AdS/CFT dual of field theory at finite temperature
- Hawking temperature T_H $\Leftrightarrow$ temperature in the dual QFT

Embedding and quark condensate

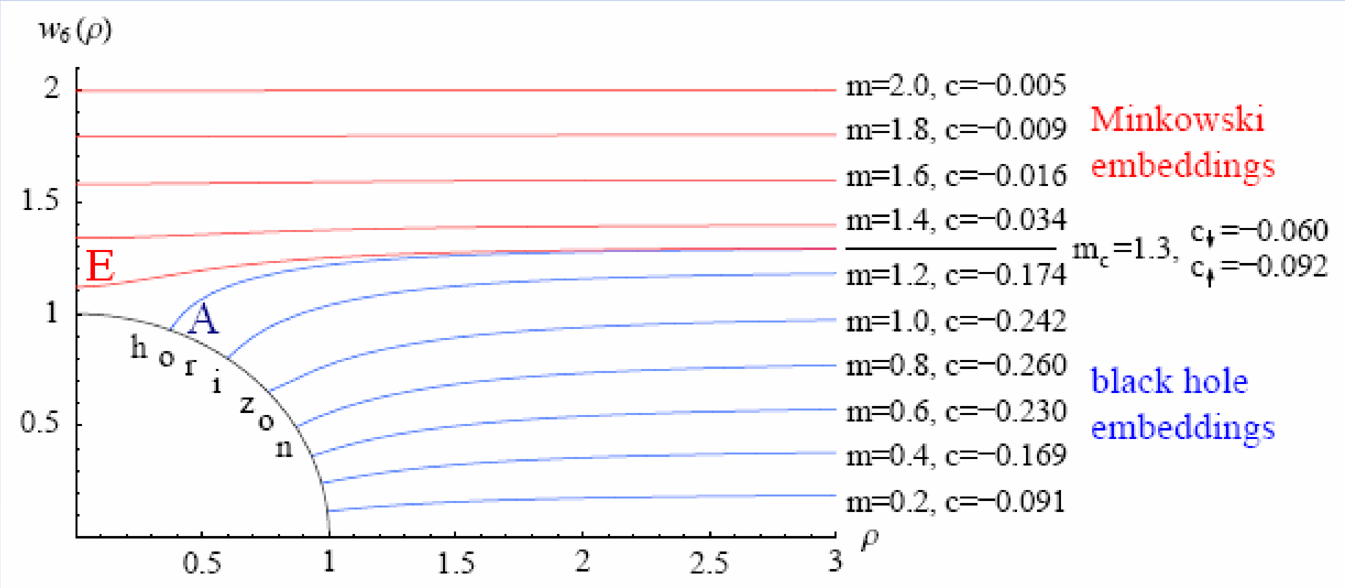
duality: i) branes in **AdS black hole** background (deconf.)
ii) „QCD-like“ SU(N) YM theory with N>>1 ($T \neq 0$)

Babington, Erdmenger, Evans, Guralnik, I.K. (2003), I.K. (2004)

Mateos, Myers, Thomson (2006)

Two kinds of embedding solutions: branes may end either on the horizon or at a point above the horizon

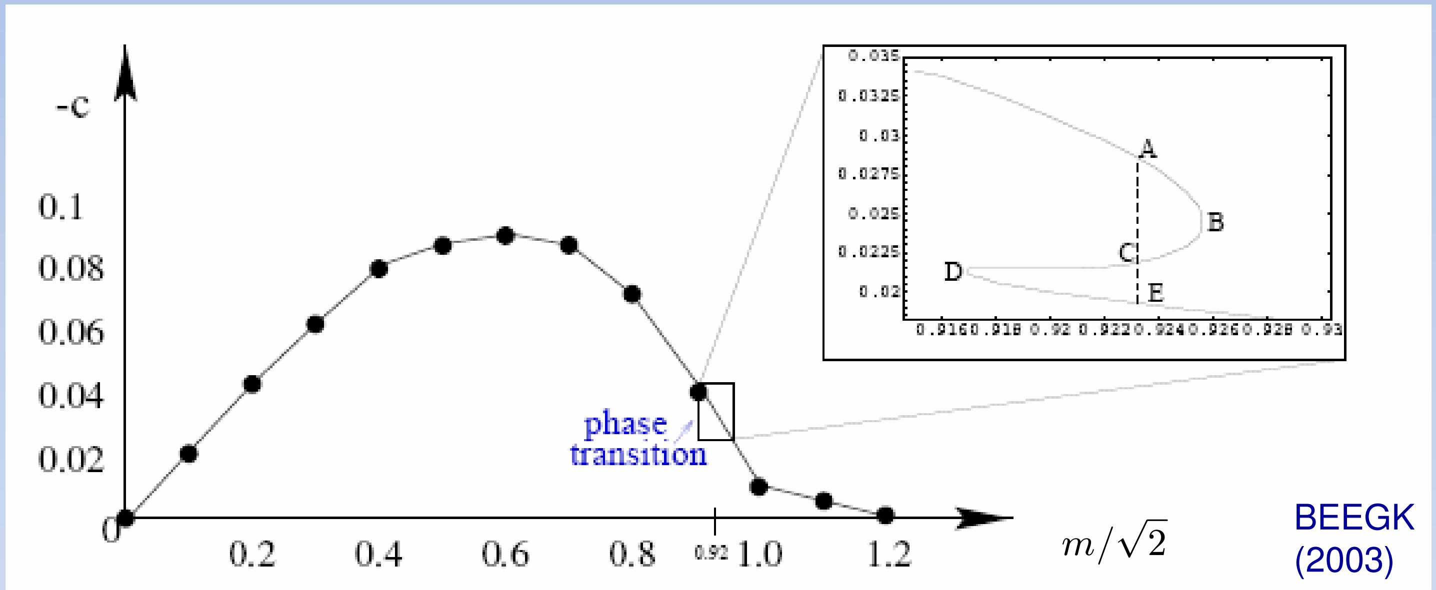
embedding profiles:



First-order phase transition

condensate vs quark mass:

I.K. (2004)



properties of the transition:

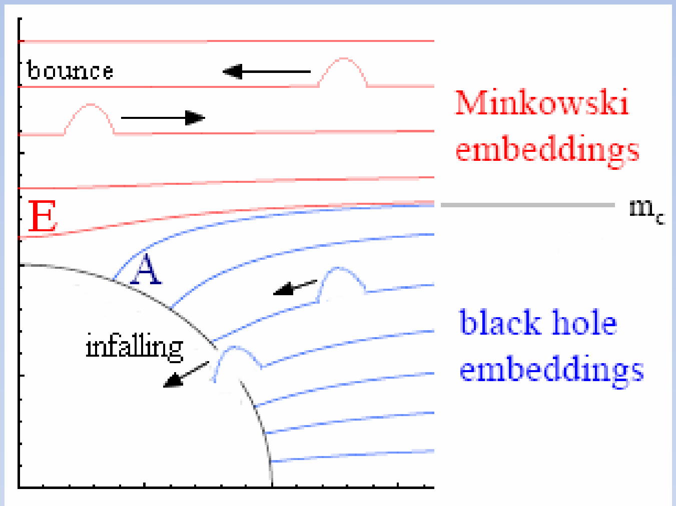
- transition occurs above conf./deconf. transition, $T_c > T_{dec}$
- first-order transition at m_c=1.3 (= 0.92 in figure)

Physical interpretation?

Meson melting into the QGP

decay governed by quasinormal modes:

Hoyos, Landsteiner, Montero (2006)



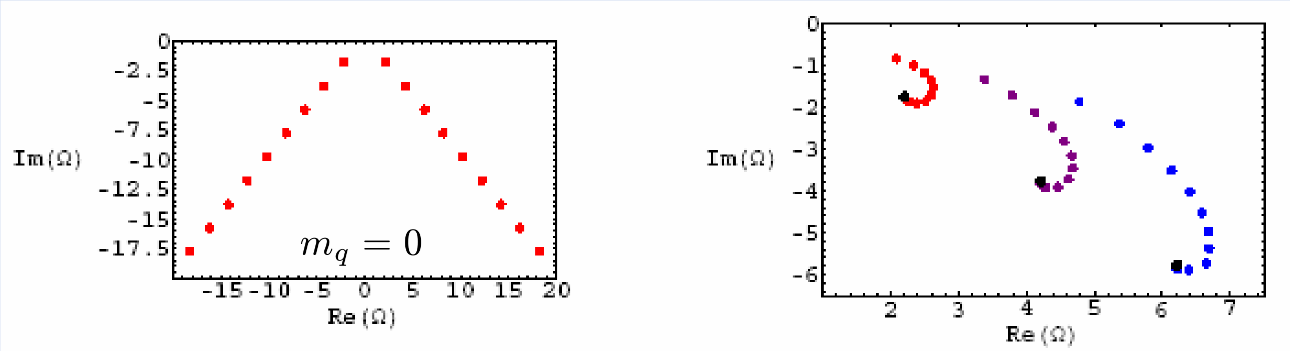
$$\delta\phi = \phi(\rho)e^{-i\omega t + ik\cdot x}$$

$$\omega_n^{\text{quasinormal}} = \Omega - i\frac{\Gamma_n}{2}$$

$\tau \sim \Gamma_n^{-1}$ relaxation time

$\Rightarrow$ qn. modes dissipate energy into the BH, mesons melt into the quark gluon plasma

Plot of Im(ω) versus Re(ω)



Finite U(1) quark number density

Quark number density n_q and U(1) chemical potential μ

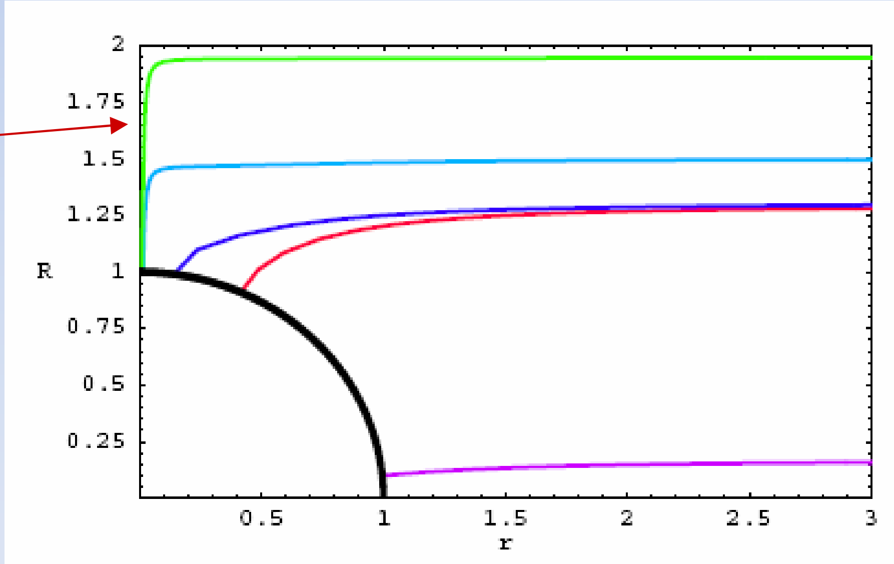
Mateos, Myers, Matsuura et al

$$A_0(\rho) = \mu + \frac{\tilde{d}}{\rho^2}\,, \qquad \tilde{d} = \frac{2^{5/2}}{N_f\sqrt{\lambda}T^3}n_q$$

(A_0 = time component of worldvolume gauge field)

For $n_q \neq 0$ all embeddings are black hole embeddings (mesons melt):

string



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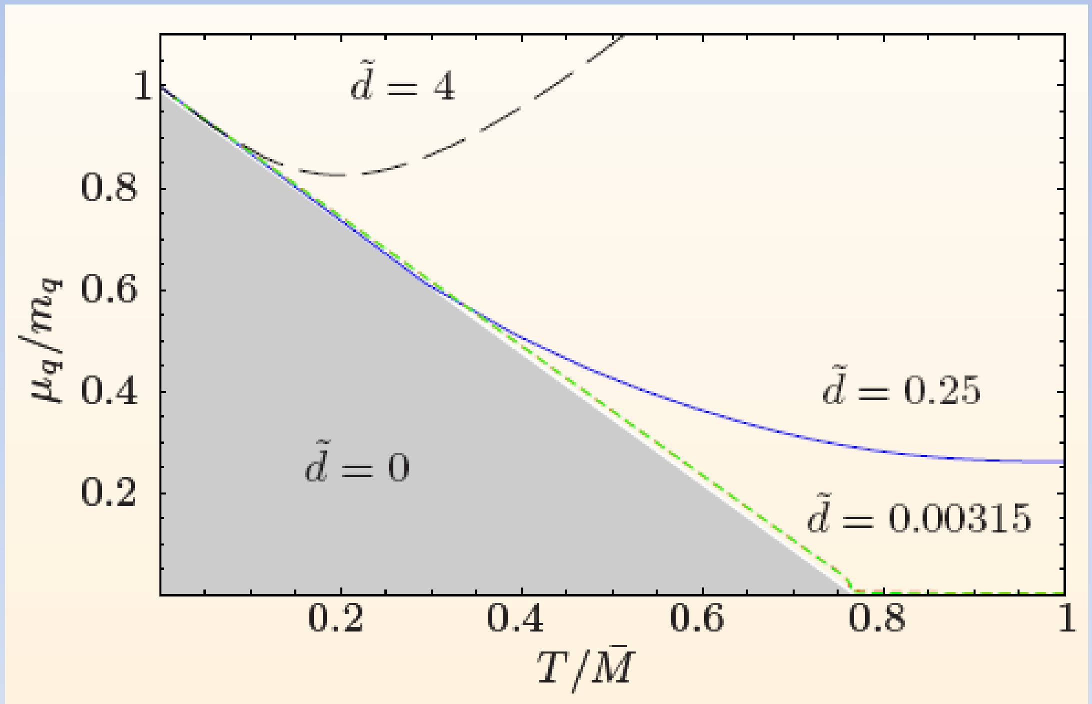
Phase diagram for finite quark number density

Phase diagram:

Sin, Yogendran et al; Mateos, Myers et al; Karch, O'Bannon; . . .



first-order transition is characterised by the condensation of charge

grey region: $n_q = 0$: Minkowski embeddings $\Rightarrow$ stable mesons
white region: $n_q \neq 0$: black hole embeddings $\Rightarrow$ meson melting

Conclusions

Generalized AdS/CFT dualities provide new tools for
strongly-coupled gauge theories

numerous applications:

- spontaneous chiral symmetry breaking

- first-order phase transition in the deconfined phase
  interpretation: meson melting in quark gluon plasma

- many others ...

Erdmenger, Evans, I. K. and Threlfall,
Review Paper (2007), EPJA