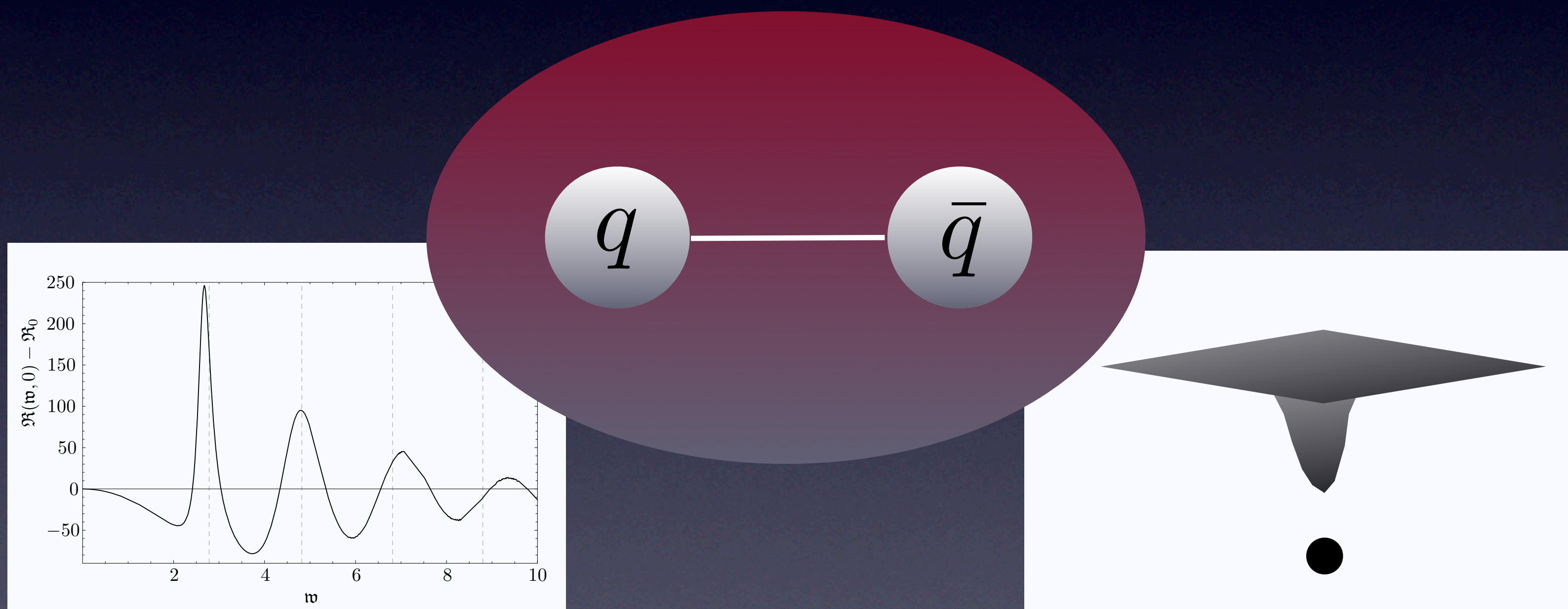
Useful results from the AdS/CFT correspondence?

-holographic quarks, mesons and the Super-Yang-Mills phase diagram



EMMI workshop ‘Quarks, Hadrons and the Phase Diagram of QCD’,
St Goar, 31st August 2009

Matthias Kaminski
IFT-UAM/CSIC Madrid

Outline

I. Invitation: AdS/QGP Correspondence

II. Quarks

III. Mesons

IV. SYM phase diagrams

V. Holographic hydrodynamics

VI. Summary

I. Invitation: AdS/QGP Correpondence

-What can we do with gauge/gravity?

- Compute observables in strongly coupled QFTs
- Meson spectra/melting
  Review: [Erdmenger,Evans,Kirsch,Threlfall 0711.4467]
- Quark energy loss, Jets
- Thermodynamics/Phase diagrams
- Holographic hydrodynamics (beyond Muller-Israel-Stewart)
- Transport coefficients (e.g. 'universal' viscosity bound)
- Model QCD equation of state ($v_s, \xi/s$ match lattice-QCD)
- Deconfinement & Break: Chiral, Conformal, SUSY
- Condensed matter applications (strongly corr. electrons)
- [AdS/QCD (bottom-up approach)]

I. Invitation: AdS/QGP Correpondence

-General features of gauge/gravity

Large N, large $\lambda = g_{\mathrm{YM}}{}^2 N$

Gauge theory	← *duality* →	Gravity theory
strong (weak)	↔	weak (strong)
d-dimensional	← *holography* →	(d+1)-dimensional
symmetries	↔	symmetries

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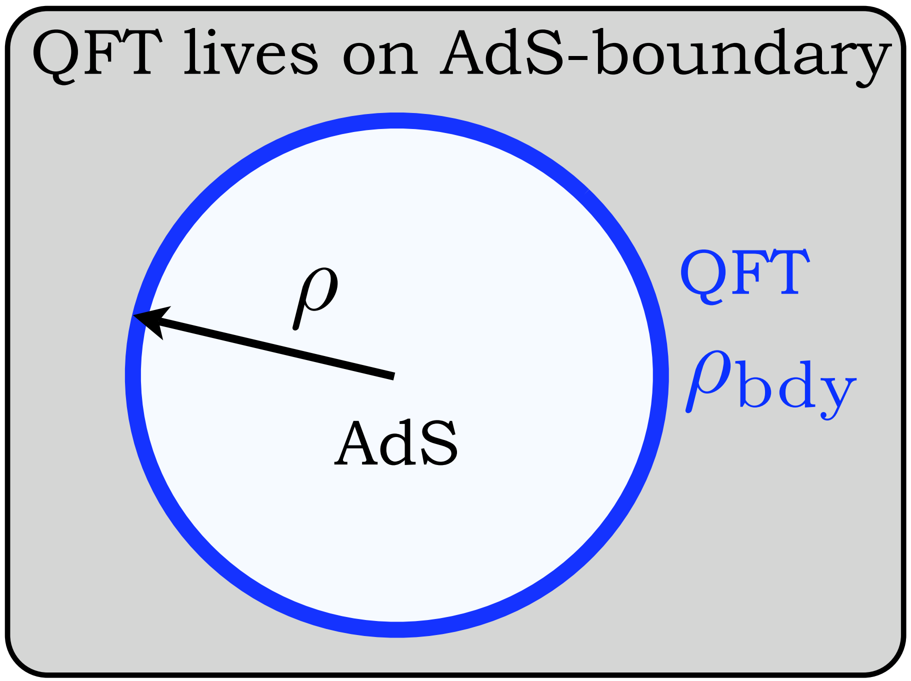

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Dictionary:

operator J_μ ⟷ field A_μ

correlator $G^{\rm ret}$ ⟷ $\dfrac{\delta^2}{\delta A_{\rm bdy}\delta A_{\rm bdy}} S_{\rm Sugra}$

QFT FEATURE ⟷ GEOMETRY

(energy scale) — (radial coord.)

(phase transition) — (geom. transition)

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symmetries	⟷	symmetries

Boundary asymptotics:

$$A = A^{(0)} + \frac{A^{(2)}}{\rho^2} + \dots$$

$A^{(0)}$: non-normalizable (source)

$A^{(2)}$: normalizable (vev)

$$A^{(2)} = \langle J \rangle$$

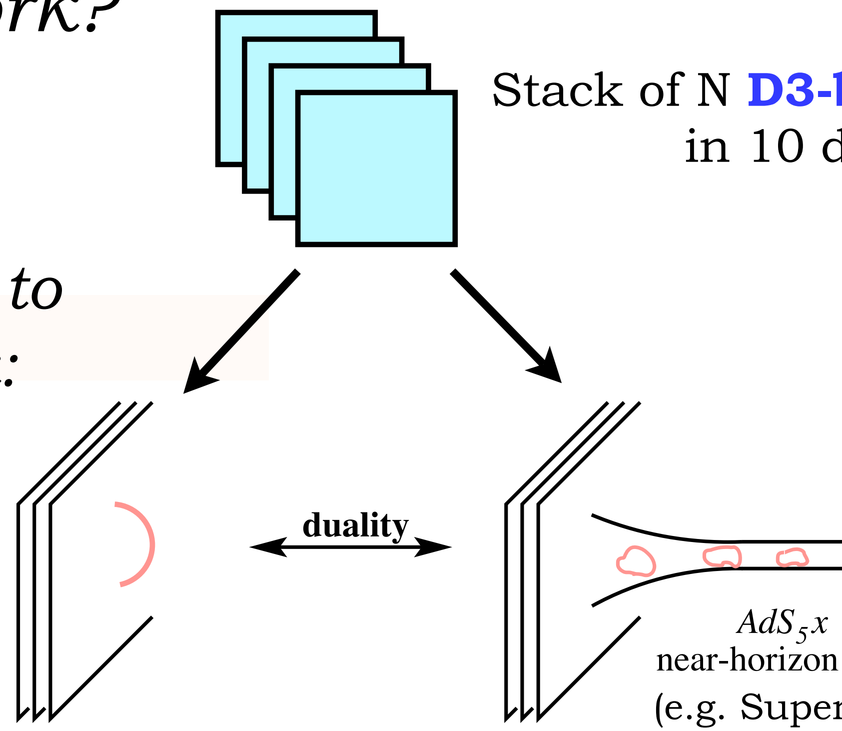
$$(\rho \to \infty)$$

I. Invitation: AdS/QGP Correspondence

-Why does it work?

Stack of N **D3-branes** (coincident) in 10 dimensions

Two distinct ways to describe this stack:



4-dimensional worldvolume theory on the D3-branes (e.g. $\mathcal{N} = 4$ Super-Yang-Mills)

gauge side

$AdS_5 x\ S^5$ near-horizon geometry

(e.g. Supergravity)

gravity side

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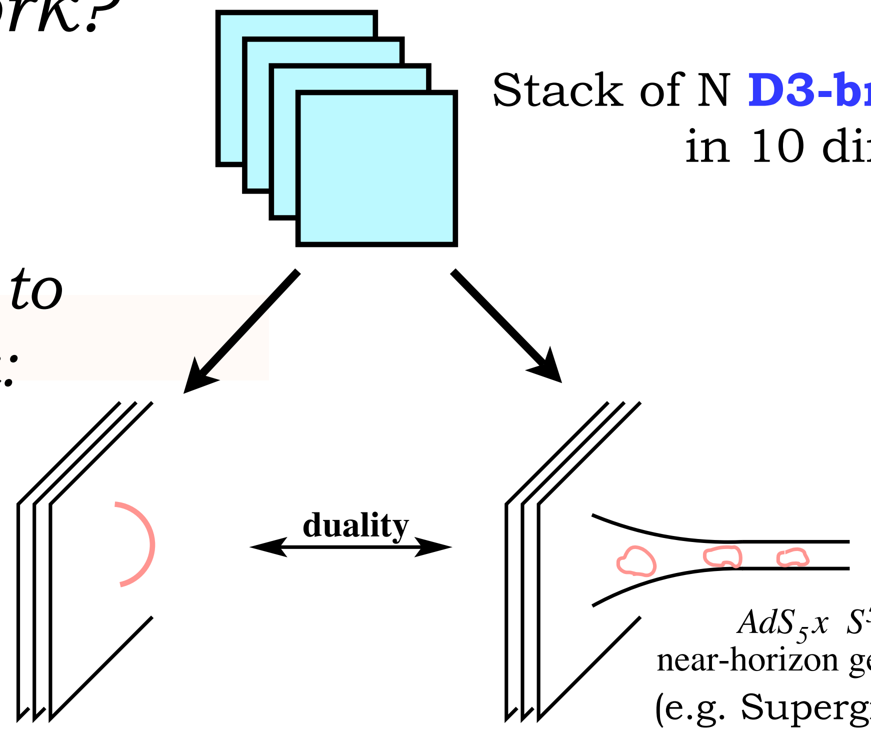

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gauge side

near-horizon geometry
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gravity side

-How does it work?

Add/change geometric objects on 'gravity side':

Geometric setup: Strings/Branes → Find solution configuration → Field Theory result

Example: Schwarzschild radius corresponds to temperature

II. Quarks

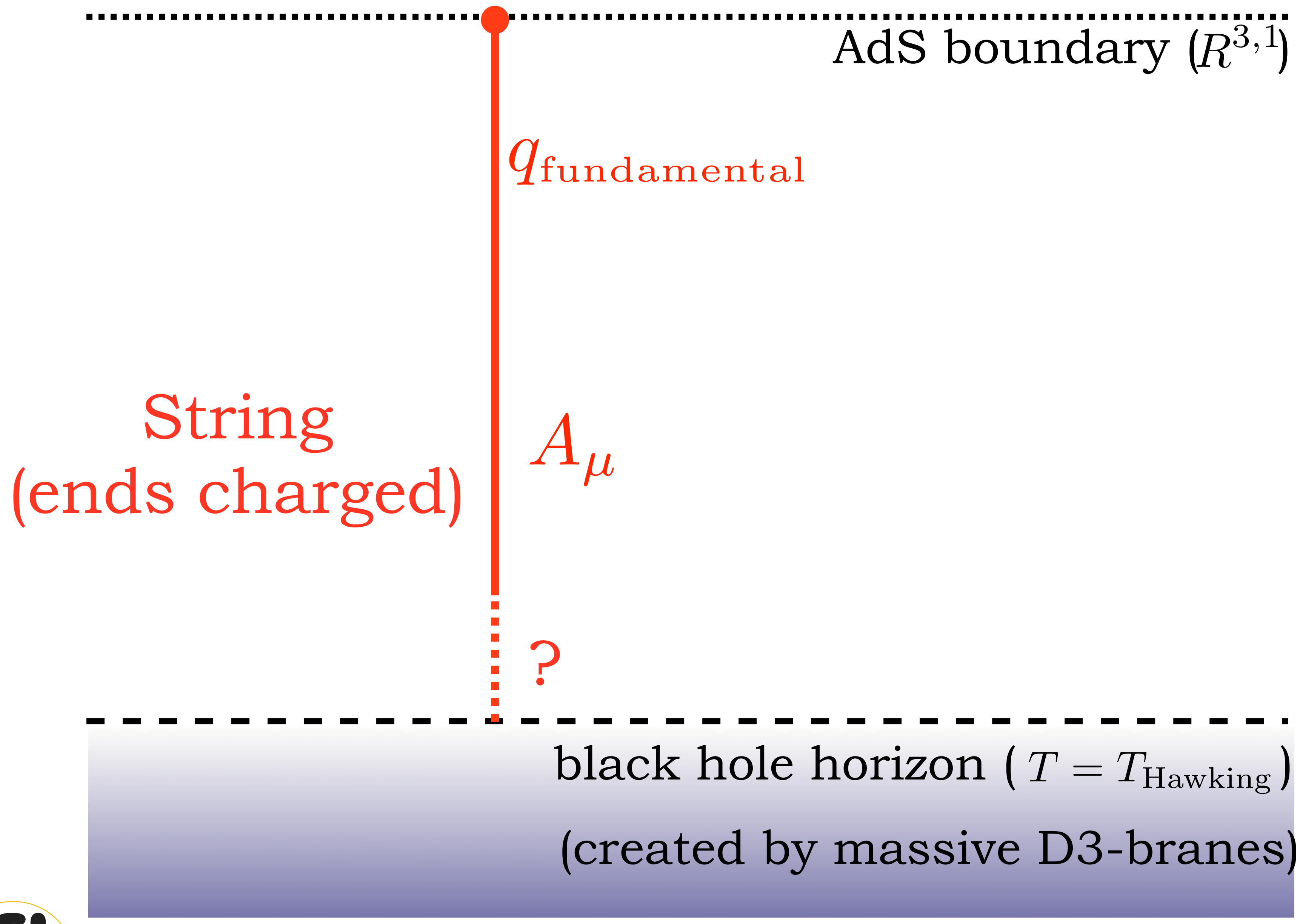
-Geometric setup

-Gravity solution

-Results

-Discussion

II. Quarks -*Geometric setup (general)*



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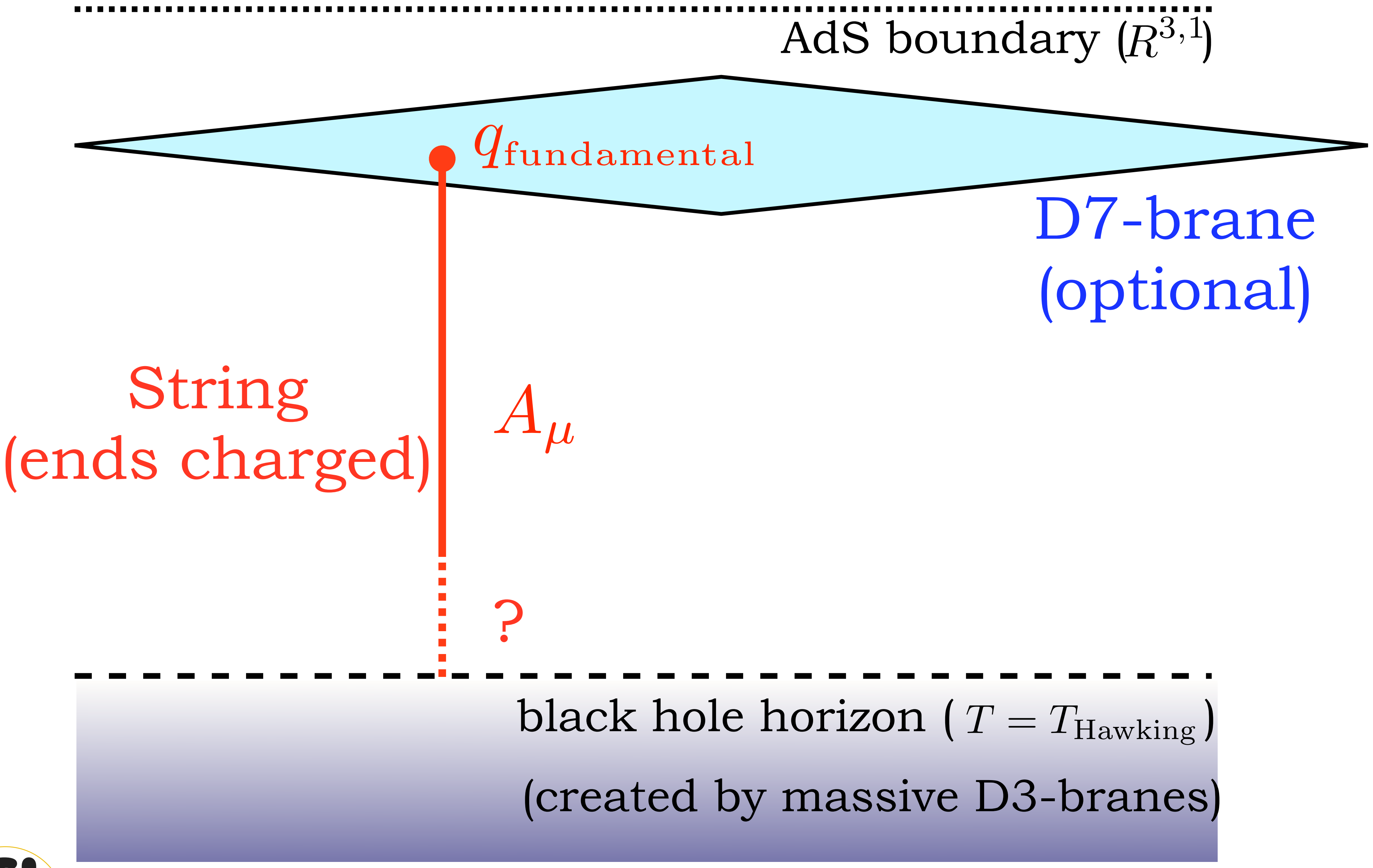
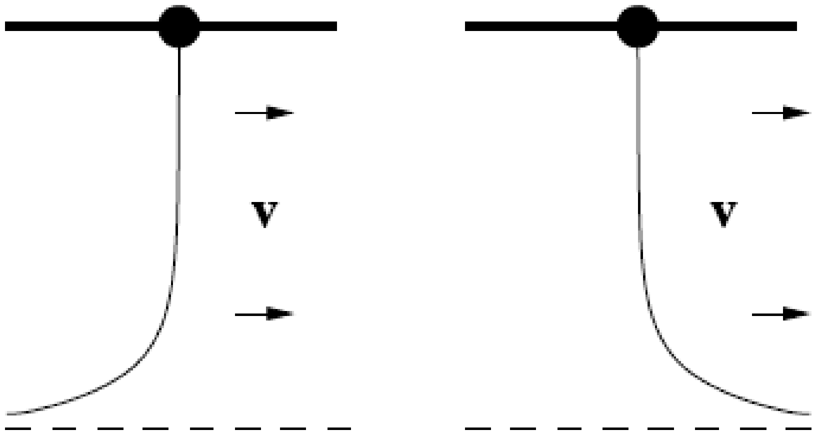


II. Quarks -*Gravity solutions & results (drag)*



[Herzog,Karch,Kovtun,Kozcaz,Yaffe hep-th/0605158]

[Casalderrey-Solana,Teaney hep-th/0605199]

[Gubser hep-th/0605182]

- left: trailing string solution
- right: unphysical
- analytic solution

- quark E,p-loss rate:

$$\frac{dp}{dt} = \frac{1}{v}\frac{dE}{dt} = -\frac{\pi}{2}\sqrt{\lambda}T^2 \frac{v}{\sqrt{1-v^2}}$$

- equilibration times:

$$\frac{dp}{dt} = -\frac{p}{\tau_q}\,, \qquad \tau_q = \frac{2m_q}{\pi T^2\sqrt{\lambda}}$$

$$\tau_{\text{charm}} \approx 2fm$$
$$\tau_{\text{bottom}} \approx 6fm$$

II. Quarks *-Discussion*

- Drag on heavy quarks in thermal SYM
- Viscous drag has upper bound: $\mu \leq 2\pi T$ $\qquad (\frac{dp}{dt} = -\mu p)$
- Mechanism: Energy & Momentum flow along string
  - not scattering (string fluctuations)
  - not glueball emission (closed string 'emission')
  - rather like a wake of a boat *[Gubser,Pufu,Yarom 0706.0213]* *[Chesler,Yaffe 0706.0368]*

Jets:

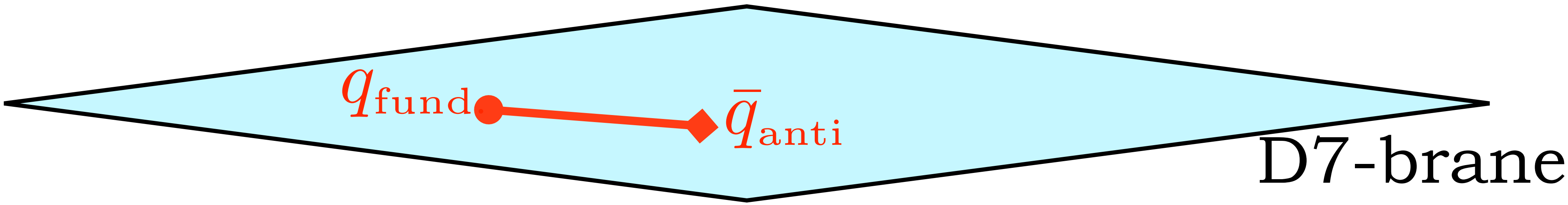
- complete energy density and flux (heavy quark at v)
- supersonic: Mach cone
- near cone: most of energy flux flows orthogonal to front
- diffusion wake behind quark
- complete computation vs hydro: hydrodynamics valid! *[Chesler]*

III. Mesons

-Geometric setup
-Gravity solution
-Results
-Discussion

III. Mesons *-Geometric setup*

- Stationary gravity 'background' gives equilibrium thermodynamics
- Gravity 'fluctuations' give field theory dynamics



short string (low-energy excitation) $\tilde{A}_\mu$ ⟷ fluctuation of corresponding current (fundamental-antifundamental) $\tilde{J}^\mu$

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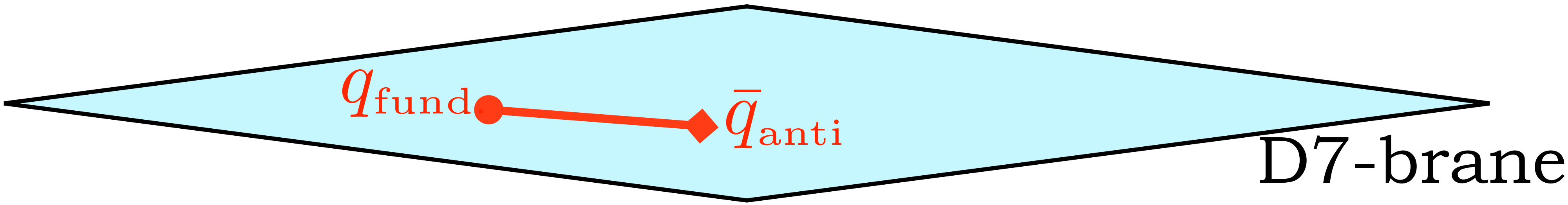

short string (low-energy excitation) $\tilde{A}_\mu$ $\longleftrightarrow$ fluctuation of corresponding current (fundamental-antifundamental) $\tilde{J}^\mu$

Chemical potential:

$$\hat{A}_\mu = \delta_{\mu 0} A_0 + \tilde{A}_\mu$$

[Nakamura et al., hep-th/0611021]
[Myers et al., hep-th/0611099]

III. Mesons *-Gravity solution*

[Erdmenger, M.K., Rust 0710.0334]

Effective action: $$S_{\mathrm{D7}} = \int \mathrm{d}^8 x \sqrt{\left|\det\{[g+F]+\tilde{F}\}\right|}\,, \quad F_{\mu\nu} = \partial_{[\mu} A_{\nu]}$$

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Equation of motion: $$0 = \tilde{A}'' + \frac{\partial_\rho[\sqrt{|\det G|}G^{22}G^{44}]}{\sqrt{|\det G|}G^{22}G^{44}}\tilde{A}' - \frac{G^{00}}{G^{44}}\varrho_H{}^2\omega^2\tilde{A}$$

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`Curved' Maxwell equations:

$$\partial_\mu F^{\mu\nu} = 0$$

$$\partial_\mu \left(\sqrt{-G} G^{\mu\nu} G^{\rho\sigma} F_{\nu\sigma}\right) = 0$$

$$\partial_\mu \left(\sqrt{-G} G^{\mu\nu} G^{\rho\sigma} \partial_{[\nu} \tilde{A}_{\sigma]}\right) = 0$$

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Translation to gauge theory by duality: $$\underset{\text{(source)}}{A_\mu} \overset{\text{AdS/CFT}}{\longleftrightarrow} J^\mu$$

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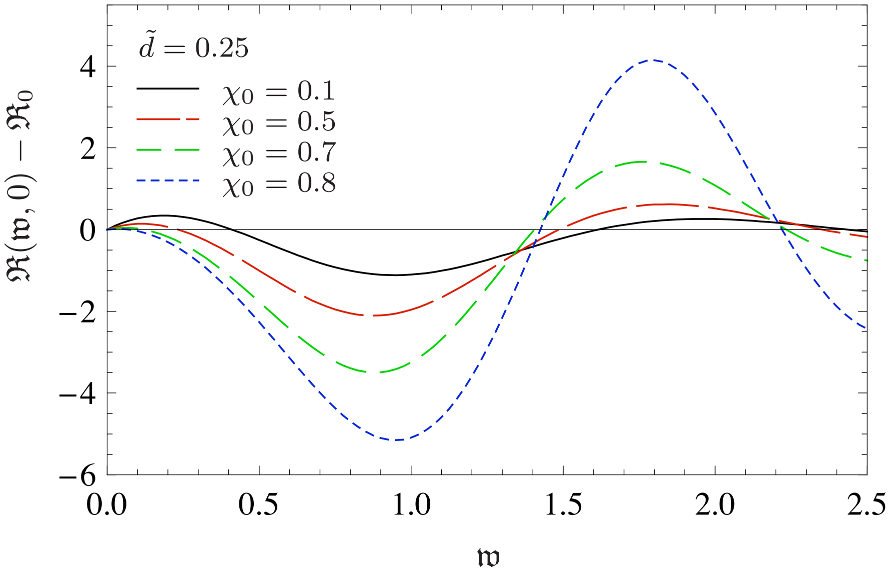
Gauge correlator: *[Son et al.'02]*

$$G^{\mathrm{ret}} = \frac{N_f N_c T^2}{8} \lim_{\rho\to\rho_{\mathrm{bdy}}} \left(\rho^3 \frac{\partial_\rho \tilde{A}(\rho)}{\tilde{A}(\rho)}\right)$$

III. Mesons *-Results*

[Erdmenger, M.K., Rust 0710.0334]

Finite baryon density:



Thermal spectral function:

$$\mathfrak{R}(\omega,\, \mathbf{q}) = -2\,\mathrm{Im}G^{\mathrm{ret}}(\omega,\, \mathbf{q})$$

$$L(\varrho) = \varrho\,\chi(\varrho)$$

$$\chi_0 = \chi(\rho)\Big|_{\rho\to\rho_H} \sim \frac{m_{\mathrm{quark}}}{T}$$

III. Mesons *-Results*

[Erdmenger, M.K., Rust 0710.0334]

Finite baryon density:

Lower temperature

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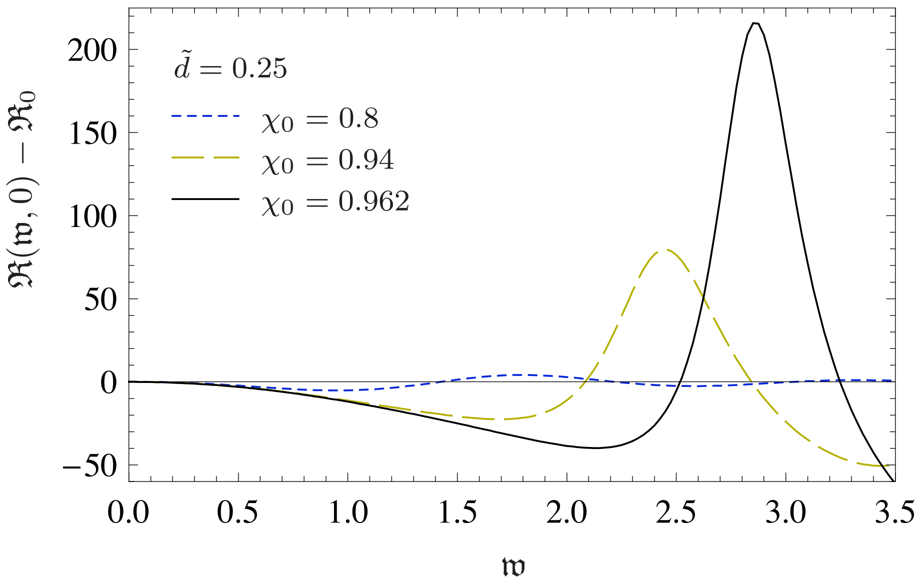

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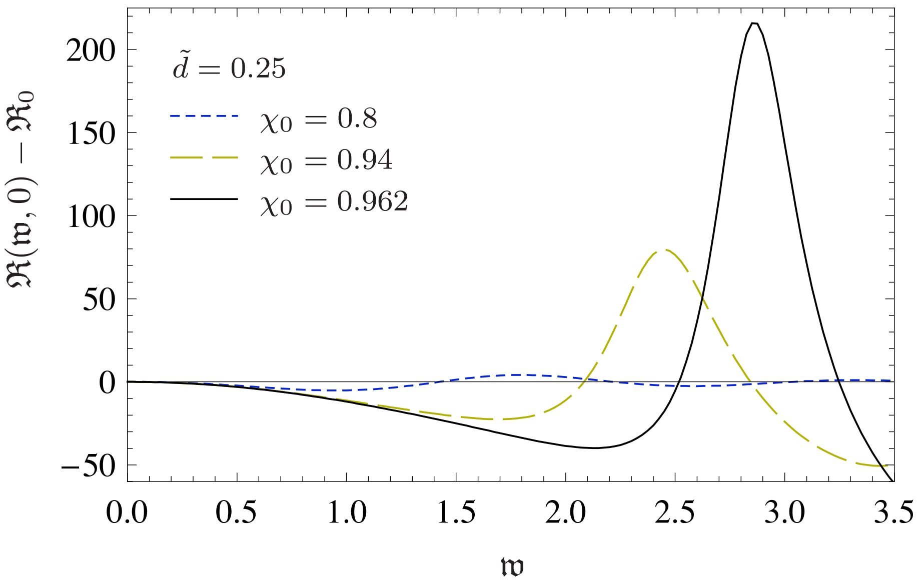

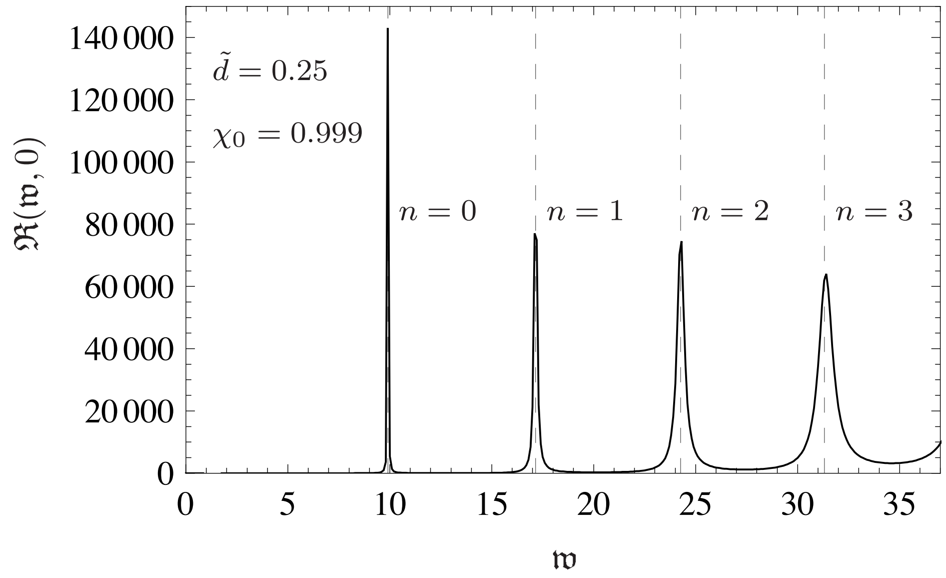

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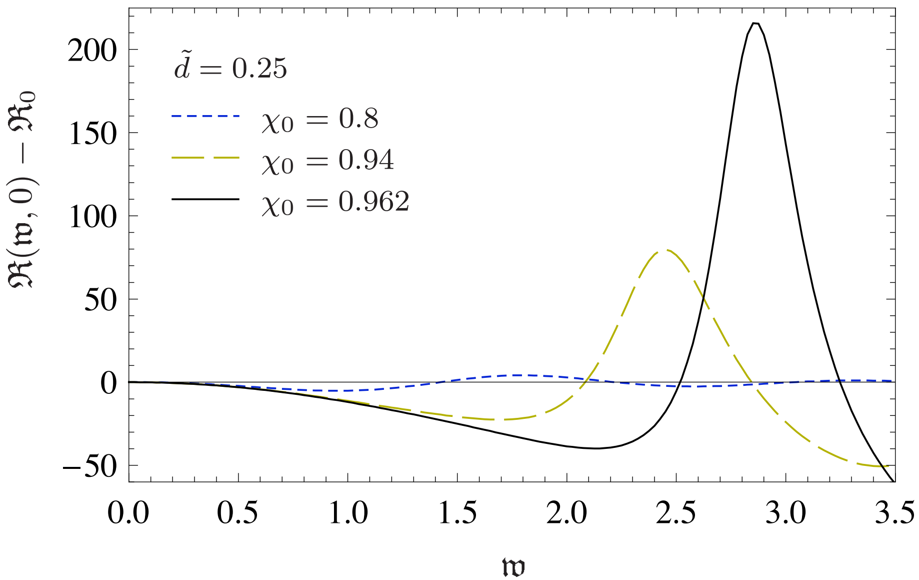

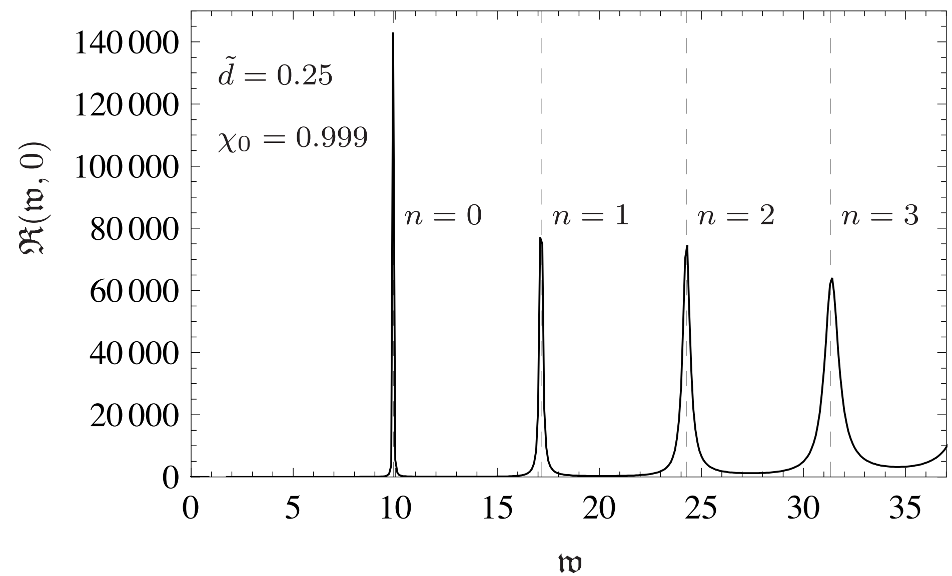

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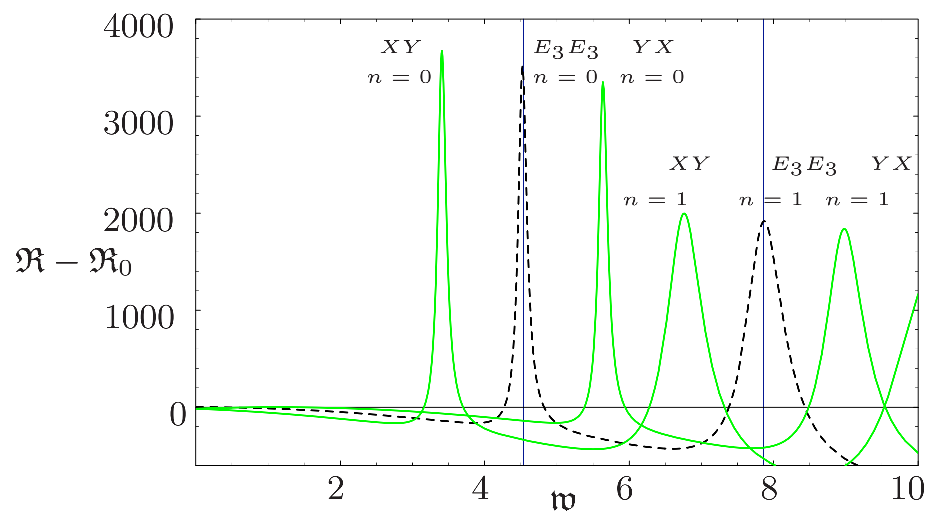

III. Mesons *-Results*

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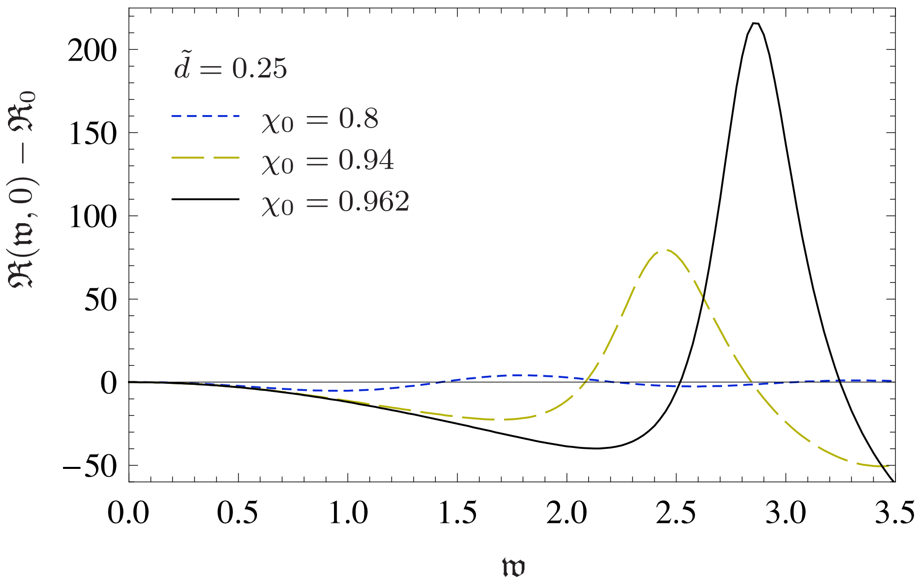

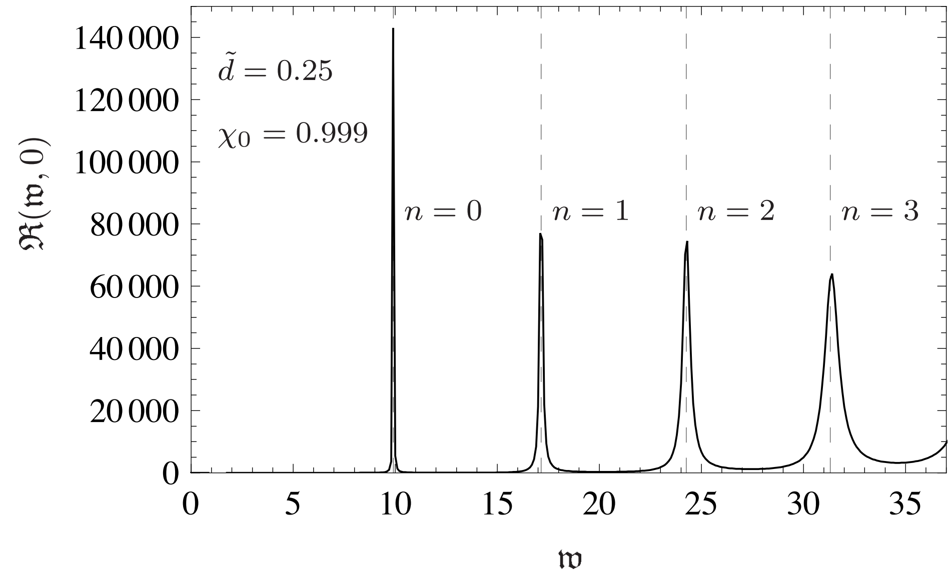

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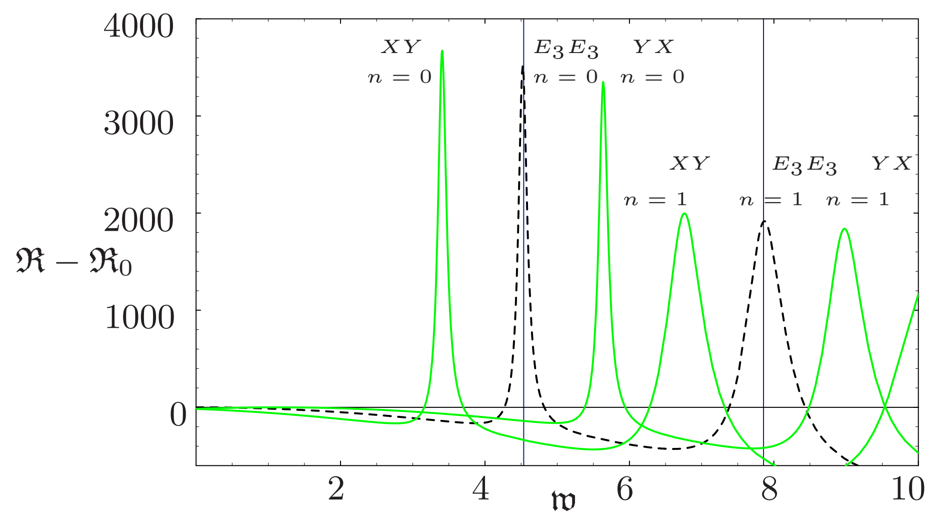


Analytically: [PhD thesis '08]

III. Mesons *-Discussion*

- Quite stable quark bound states survive deconfinement
- Resonances: vector mesons (like QCD's Rho-meson)
- Correlators encode transport coefficients (Kubo formulae)
- Poles of correlators in complex frequency plane are QNMs

Other hadron results: *Review: [Erdmenger,Evans,Kirsch,Threlfall 0711.4467]*

- Charmonium diffusion supressed at strong coupling:

[Dusling,Erdmenger, M.K., Rust,Teaney,Young 0808.0957]

$$\frac{dp_i}{dt} = \xi_i(t) - \eta_D p_i$$

$$\tau_{\text{relax}}^{\text{strong}} \approx 4\tau_{\text{relax}}^{\text{weak}}$$

- Baryons modeled by classical solutions *[Witten, hep-th/9805112]*
  - Problem: N quarks needed, N large *[Sfetsos,Siampos 0807.0236]*
  - Even worse: baryons with less than N quarks allowed

IV. Super-Yang-Mills Phase Diagrams

IV. Super-Yang-Mills phase diagram

-Gravity setup

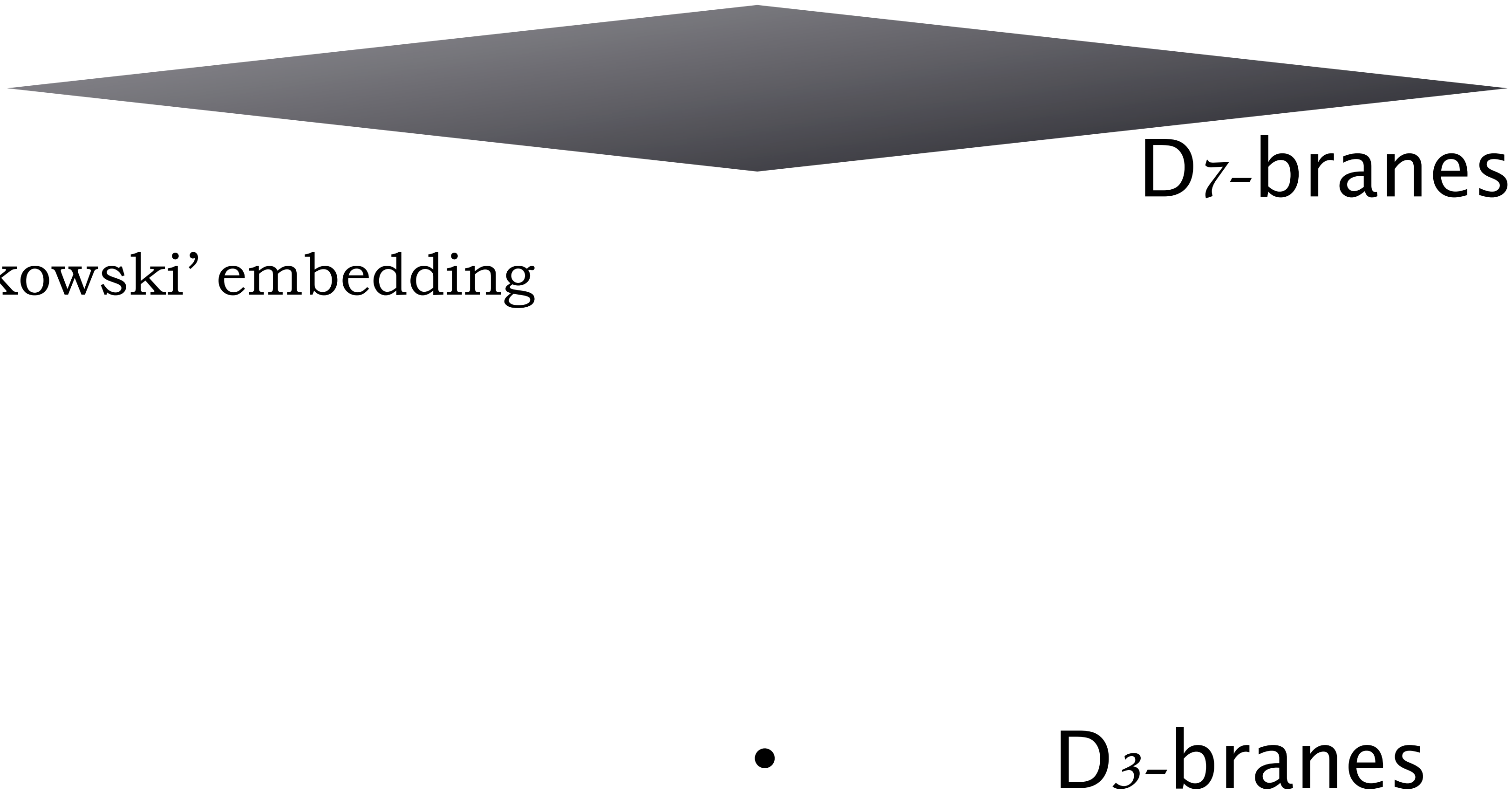
- D_3-branes

[Karch, Katz; hep-th/0205236]

IV. Super-Yang-Mills phase diagram

-Gravity setup

'Minkowski' embedding



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IV. Super-Yang-Mills phase diagram

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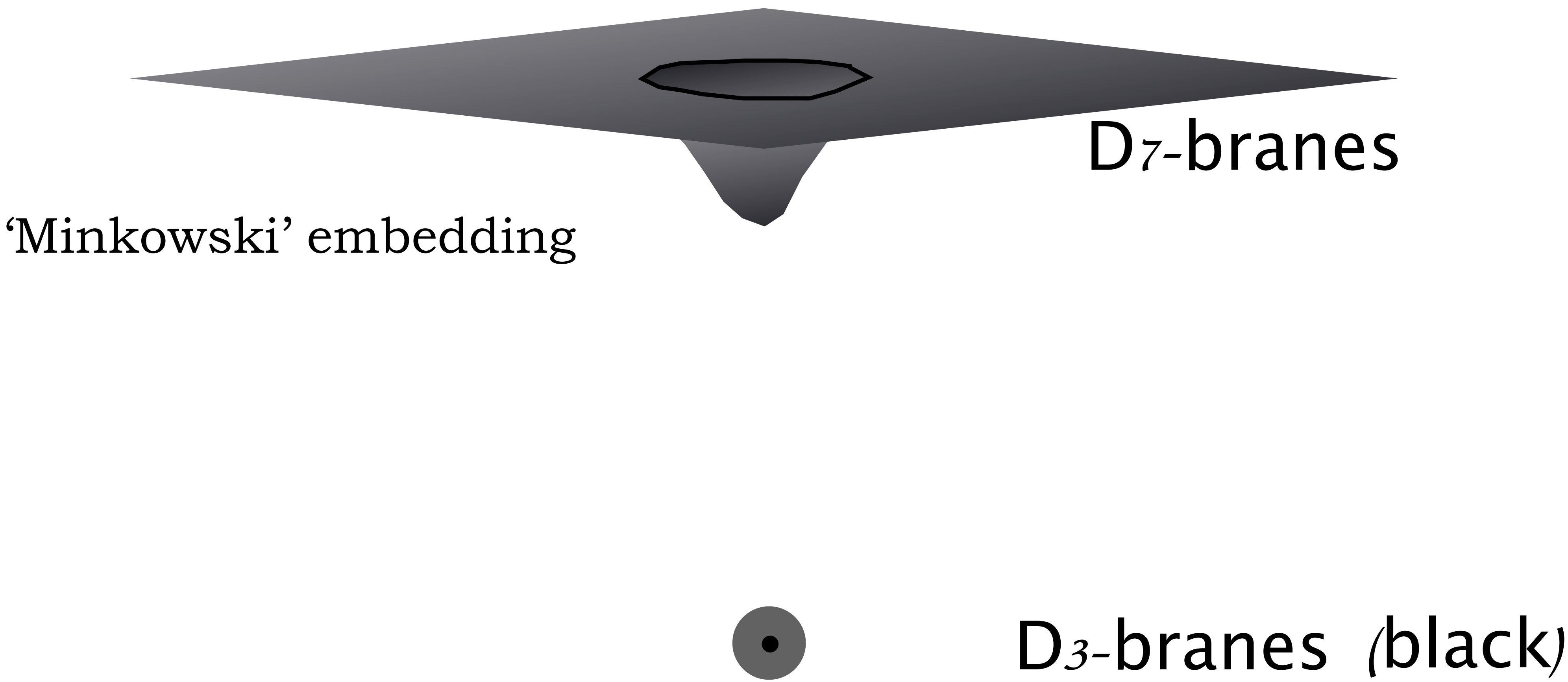

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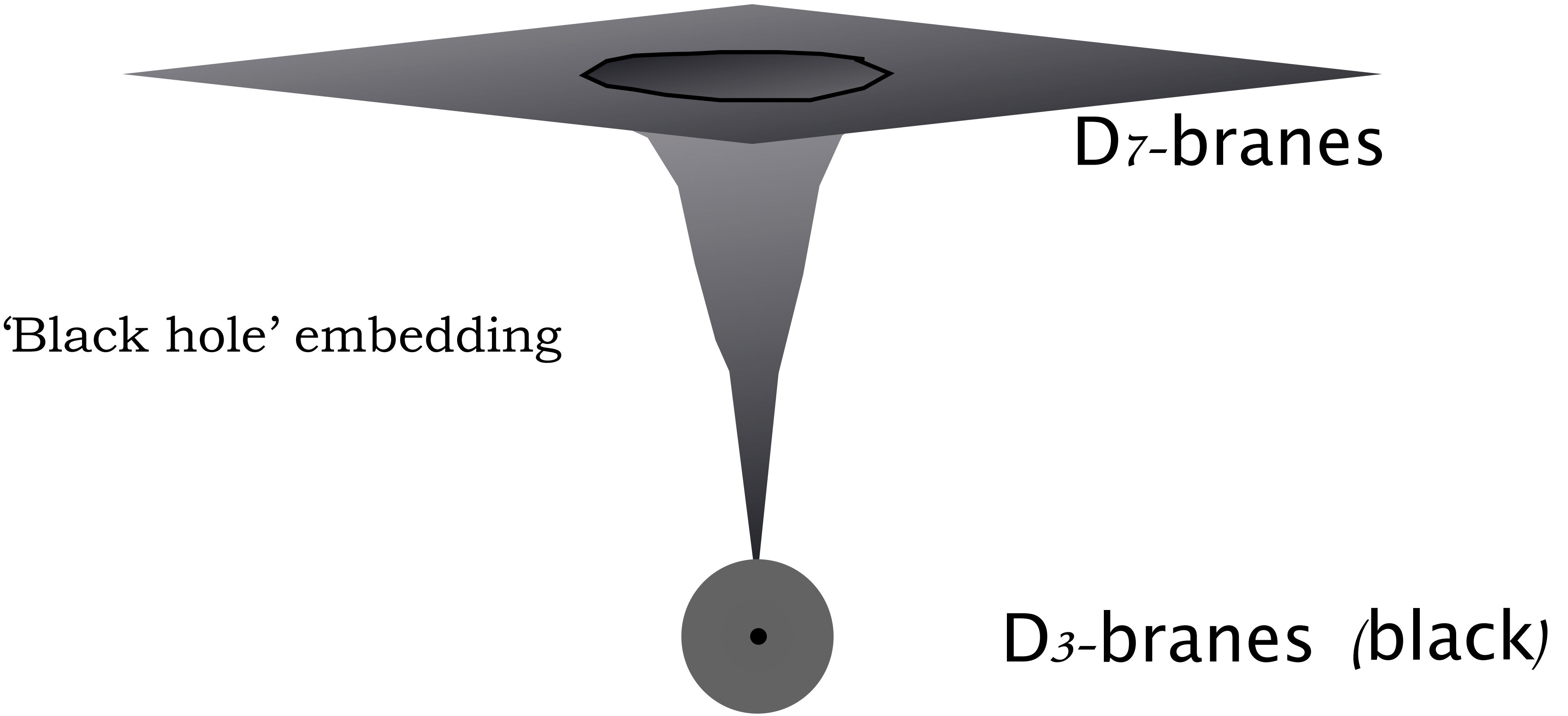

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IV. Super-Yang-Mills phase diagram

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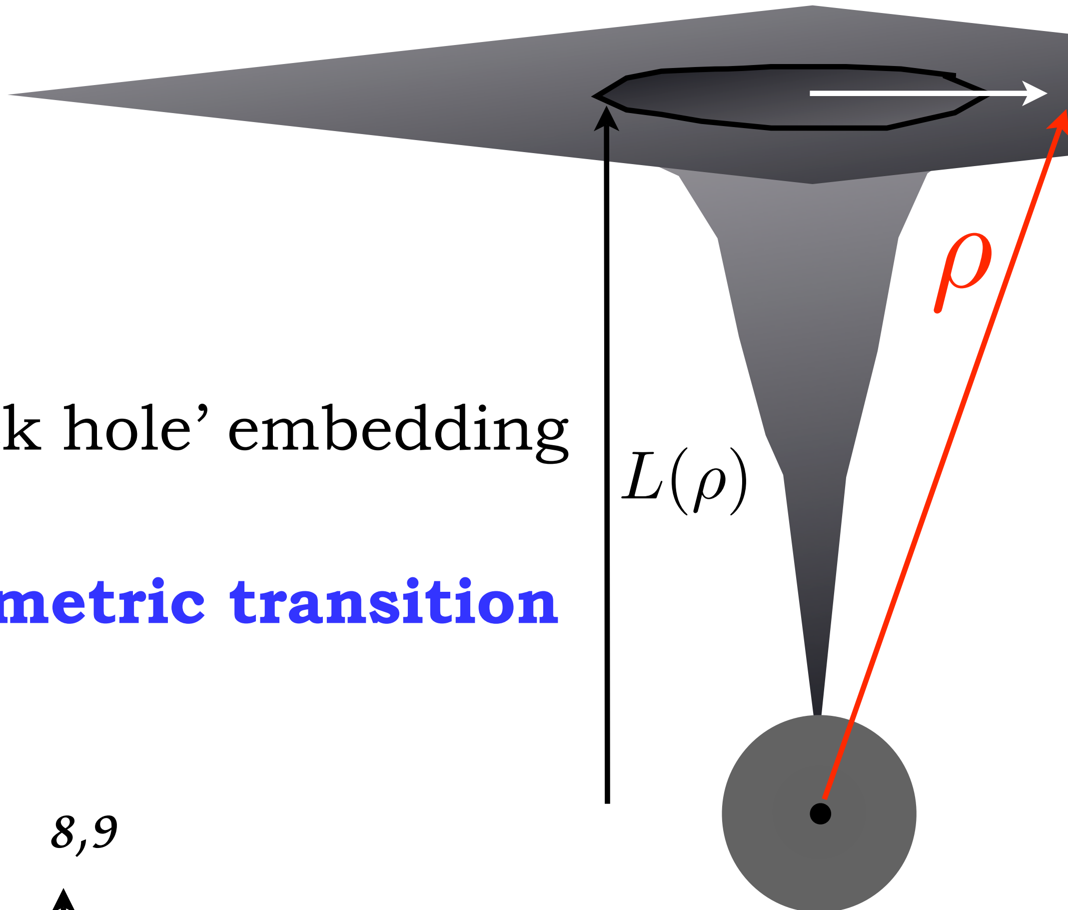


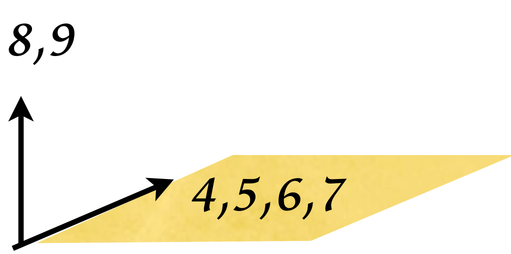
D7-branes

‘Black hole’ embedding

Geometric transition

	0	1	2	3	4	5	6	7	8	9
D3	x	x	x	x						
D7	x	x	x	x	x	x	x	x		

D3-branes (black)



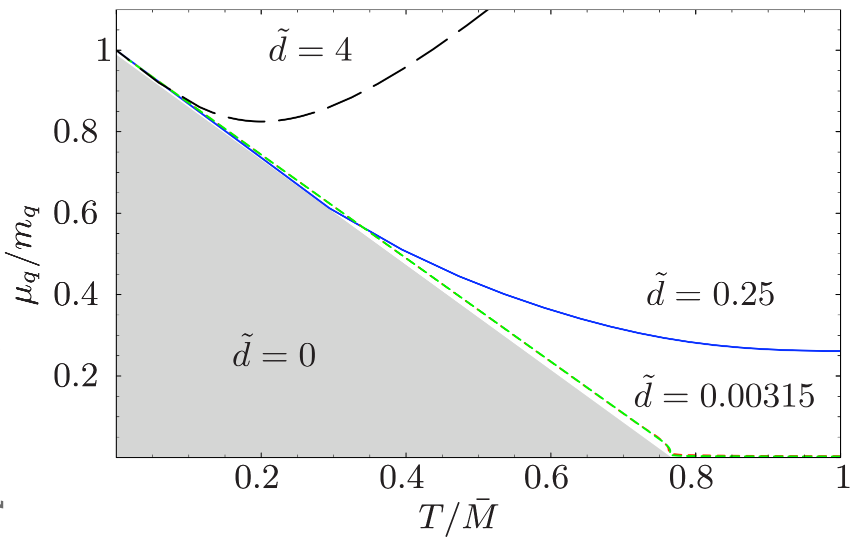
[Karch, Katz; hep-th/0205236]

IV. Super-Yang-Mills phase diagram *-Results*

Baryonic phase diagram:

[Erdmenger, M.K., Rust 0710.0334]
[Myers et al., hep-th/0611099]

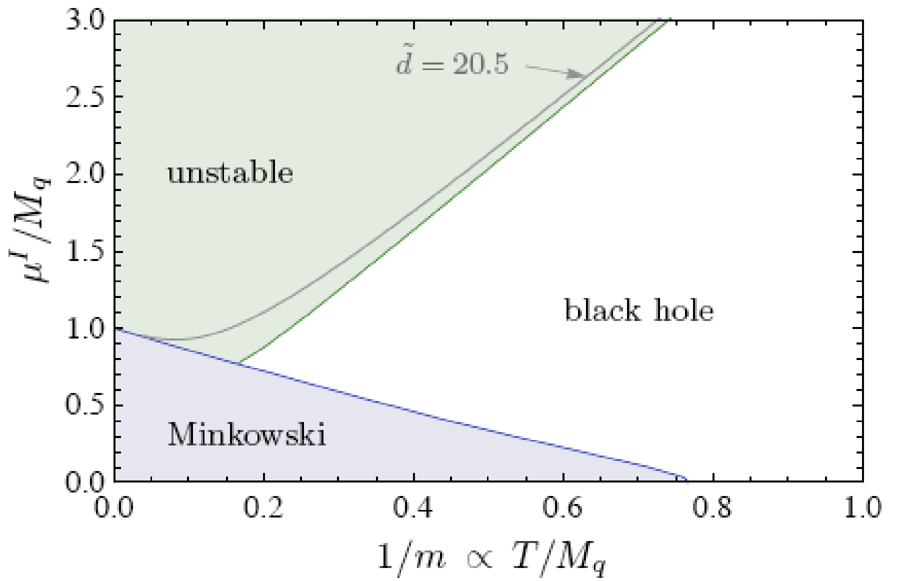
[Karch, O'Bannon '07]



- meson melting transition
- continuous range
- first order range
- no confinement

Isospin phase diagram:

[Erdmenger, M.K., Kerner, Rust 0807.2663]



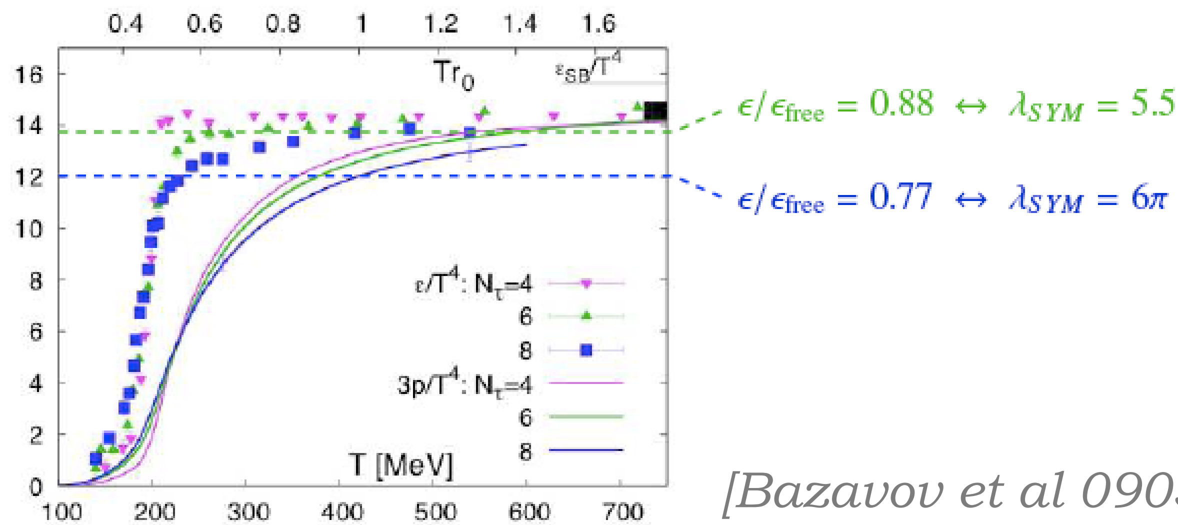
- meson melting
- flavor fluct. instability
- superconducting phase

[Ammon,Erdmenger, M.K., Kerner 0903.1864]

IV. Super-Yang-Mills phase diagram

-How useful are these SYM results?

- SYM-coupling not running
- Finite T: SUSY broken, non-conformal, BUT: large N
- Energy densities (free theories): $\epsilon_{\rm SYM} = 39T^4 \gg \epsilon_{\rm QCD} = 16T^4$
- SYM vs QCD equation of state:



[Bazavov et al 0903.4379]

- QCD-equation of state modeled with gravity potential; speed of sound and bulk viscosity similar to lattice-QCD

IV. Super-Yang-Mills phase diagram

-Other phases at strong coupling

- Sakai-Sugimoto model (D4, D8 and anti-D8-branes)
  - chiral symmetry breaking (CSB)
  - deconfinement can be tuned to coincide with CSB

- Short thermalization times: ($\tau_{\text{RHIC, therm}} = 0.6 fm/c$)

  $\tau_{\text{therm}} = 0.4 fm/c$ *[Friess et al. hep-th/0611005]*

  $\tau_H = 0.3 fm/c$ *[Amado et al. 0710.4458]*

- Black hole formation (far-from-eq. isotropization)

  [Chesler,Yaffe 0812.2053]

V. Conformal hydrodynamics
-First order hydrodynamics

Conservation equations

$$\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu j^\mu = 0$$

Constitutive equations

$$T^{\mu\nu} = \frac{\epsilon}{3}(4u^\mu u^\nu + g^{\mu\nu}) + \Pi^{\mu\nu}$$

$$j^\mu = n u^\mu - \sigma T (g^{\mu\nu} + u^\mu u^\nu)\partial_\nu \left(\frac{\mu}{T}\right) + \xi \omega^\mu$$

$$\omega^\mu = \frac{1}{2}\epsilon^{\mu\nu\lambda\rho} u_\nu \partial_\lambda u_\rho$$

[Erdmenger,Haack, M.K. ,Yarom 0809.2488]

New vorticity term arises!
(related to triangle anomaly $\partial_\mu j^\mu = -\frac{1}{8} C \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta}$)

$$\xi = C\left(\mu^2 - \frac{2}{3}\frac{\mu^3 n}{\epsilon + P}\right)$$

[Son,Surowka 0906.5044]

(see also chiral magnetic effect)
[talk by H.J.Warringa]

V. Conformal hydrodynamics

- New coefficient at first order hydrodynamics (~viscosity)
- ξ completely determined by C and equation of state
- 3 ways to compute ξ:
  - E, p conservation & Weyl symmetry (conf.rescaling)
  - positivity of entropy current (anomaly requires new coeff)
  - directly in specific holographic model (microscopic)
- Second order hydro: even more new terms (beyond MIS)

[see also talk by Rischke]

→ Relativistic hydrodynamics needs to be completed.

VI. Summary

- Perils: large N & ‘t Hooft coupling (conformality, SUSY)
- Terrifying agreement with lattice & ‘QCD’
- Heavy quarks: jets & drag (viscosity bound)
- Vector mesons survive deconfinement
- Baryon/Isospin phase diagrams with meson melting
- Flavor superconducting phase at high isospin density
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Answer: YES!

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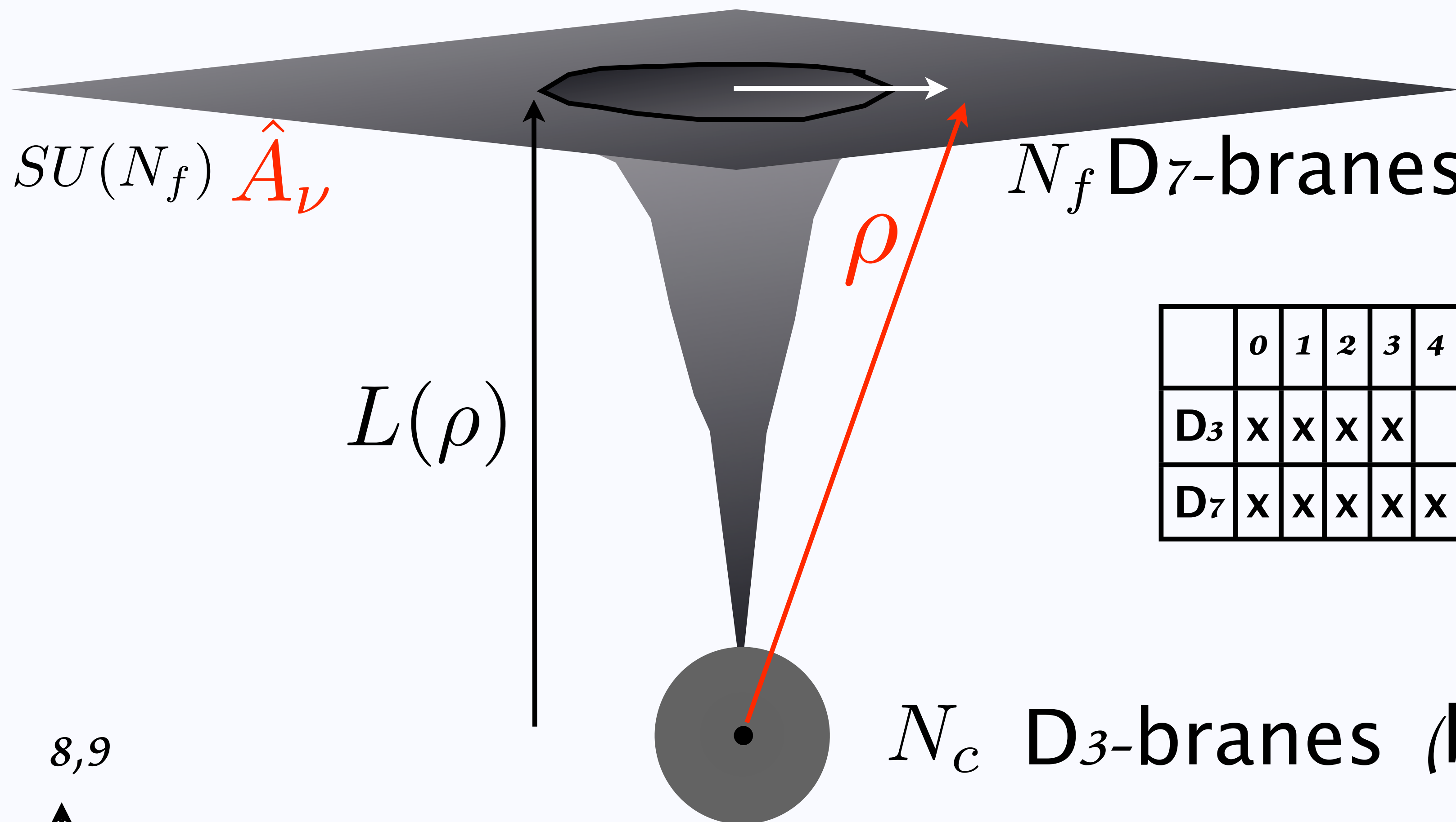
→ *Useful results from the AdS/CFT correspondence?*

Answer: YES!

APPENDIX: *-Geometric setup (detailed)*

[Karch, Katz; hep-th/0205236]



	0	1	2	3	4	5	6	7	8	9
D3	x	x	x	x						
D7	x	x	x	x	x	x	x	x		

Chemical potential: $\hat{A}_\mu = \delta_{\mu 0} A_0 + \tilde{A}_\mu$

[Nakamura et al., hep-th/0611021]
[Myers et al., hep-th/0611099]

APPENDIX: Extension of the correspondence

		Universality	Original AdS/CFT correspondence	AdS Schwarzschild black hole (D3/D7)
Gauge		QCD	$\mathcal{N}=4$ SuperYangMills	thermal Yang-Mills
Gravity		?	Type II Sugra in AdS	TypeII Sugra in AdS Schwarzschild b.h.
Gauge theory symmetry	non-conf.	✓	⊙	✓
	non-SUSY	✓	⊙	✓
Relations				$T \leftrightarrow$ horizon $\mu_B\,,\ \mu_I \leftrightarrow A_0(\rho)$

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