

# Applications of Holography in Hot Strongly Coupled Plasmas

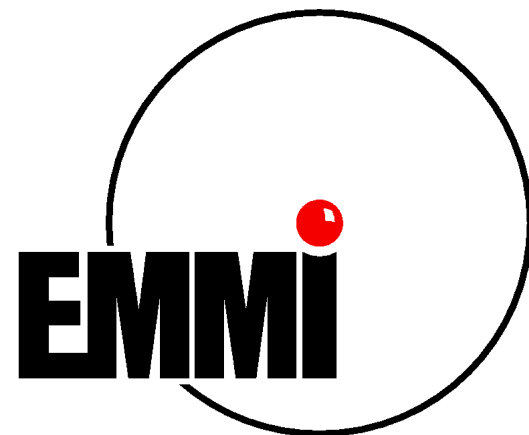


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INTERNATIONAL  
MAX PLANCK  
RESEARCH SCHOOL

PT  
FS  
FOR PRECISION TESTS  
OF FUNDAMENTAL  
SYMMETRIES

in collaboration with Carlo Ewerz



- Physics Days 2011  
GSI, Darmstadt

# Holography, Gauge/Gravity duals, AdS/CFT correspondence, ...

Heavy ion collisions and **AdS/CFT**

PHYSICAL REVIEW D **84**, 065009 (2011)

**Model of a Fermi liquid using gauge-gravity duality**

Subir Sachdev

Department of Physics

PHYSICAL REVIEW D **83**, 066004 (2011)

**Vortex flow for a holographic superconductor**

Faculty of Engineering

PHYSICAL REVIEW D **81**, 115004 (2010)

**AdS/QCD model from an effective action for open string tachyons**

Department of Physics  
(R)

Ioannis Iatrakis,<sup>1</sup> Elias Kiritsis,<sup>1,2</sup> and Ángel Paredes<sup>3</sup>

We use gauge-gravity duality to study a Fermi liquid, driven by an anti-de Sitter black hole. The Luttinger relations follow from Gauss's law. Landau's Fermi liquid theory and wall boundary conditions are also evaluated just below the transition.

DOI: [10.1103/PhysRevD.83.066004](https://doi.org/10.1103/PhysRevD.83.066004)

We investigate energy dissipation in a superconductor model corresponding to an application of constant magnetic field. We find the vortex-flow resistance and the characteristic feature of the Ginzburg-Landau (TDGL) theory of the second-order phase transition. The results are also evaluated just below the transition.

DOI: [10.1103/PhysRevD.83.066004](https://doi.org/10.1103/PhysRevD.83.066004)

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(Received 22 March 2010; published 10 June 2010)

We construct a new, simple phenomenological model along the lines of AdS/QCD. The essential new ingredient is the brane-antibrane effective action including the open string tachyon proposed by Sen [*Phys. Rev. D* **68**, 066008 (2003)]. Chiral symmetry breaking happens because of tachyon dynamics. We fit a large number of low-spin meson masses at the 10%–15% level. The only free parameters involved in the fits correspond to the overall QCD scale and the quark masses. Several aspects of previous models are qualitatively improved.

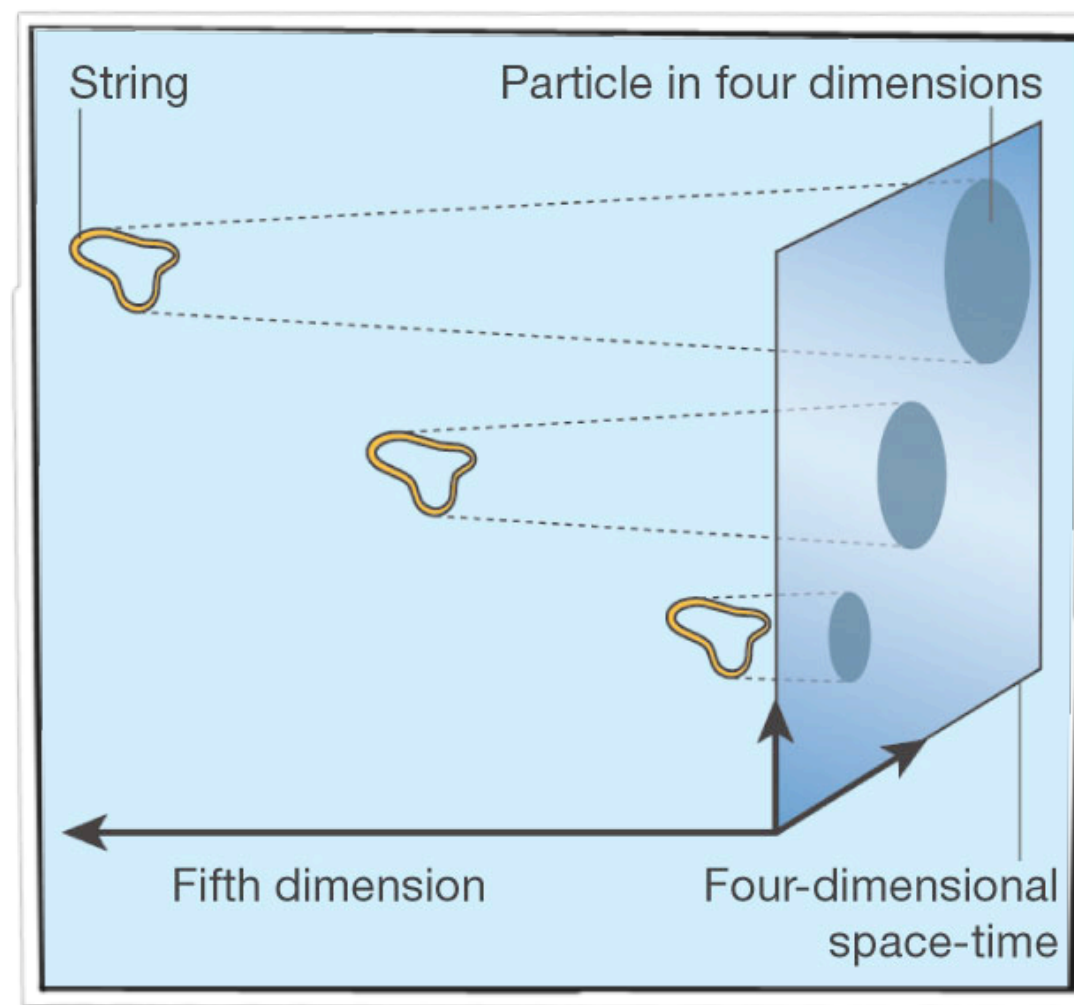
DOI: [10.1103/PhysRevD.81.115004](https://doi.org/10.1103/PhysRevD.81.115004)

PACS numbers: 11.25.Tq, 11.25.Wx, 12.38.Lg, 12.40.Yx

*...many realisations, but one concept.*

# Holographic Principle

*The physics in a  $(d+1)$ -dimensional volume can be described by a theory living on the  $d$ -dimensional boundary.*



Maldacena, 2003

- e.g.: duality between gauge theories in  $d$ -dimension and gravity theories (string theories) in higher dimensions.



# Practical Realisation of Holography

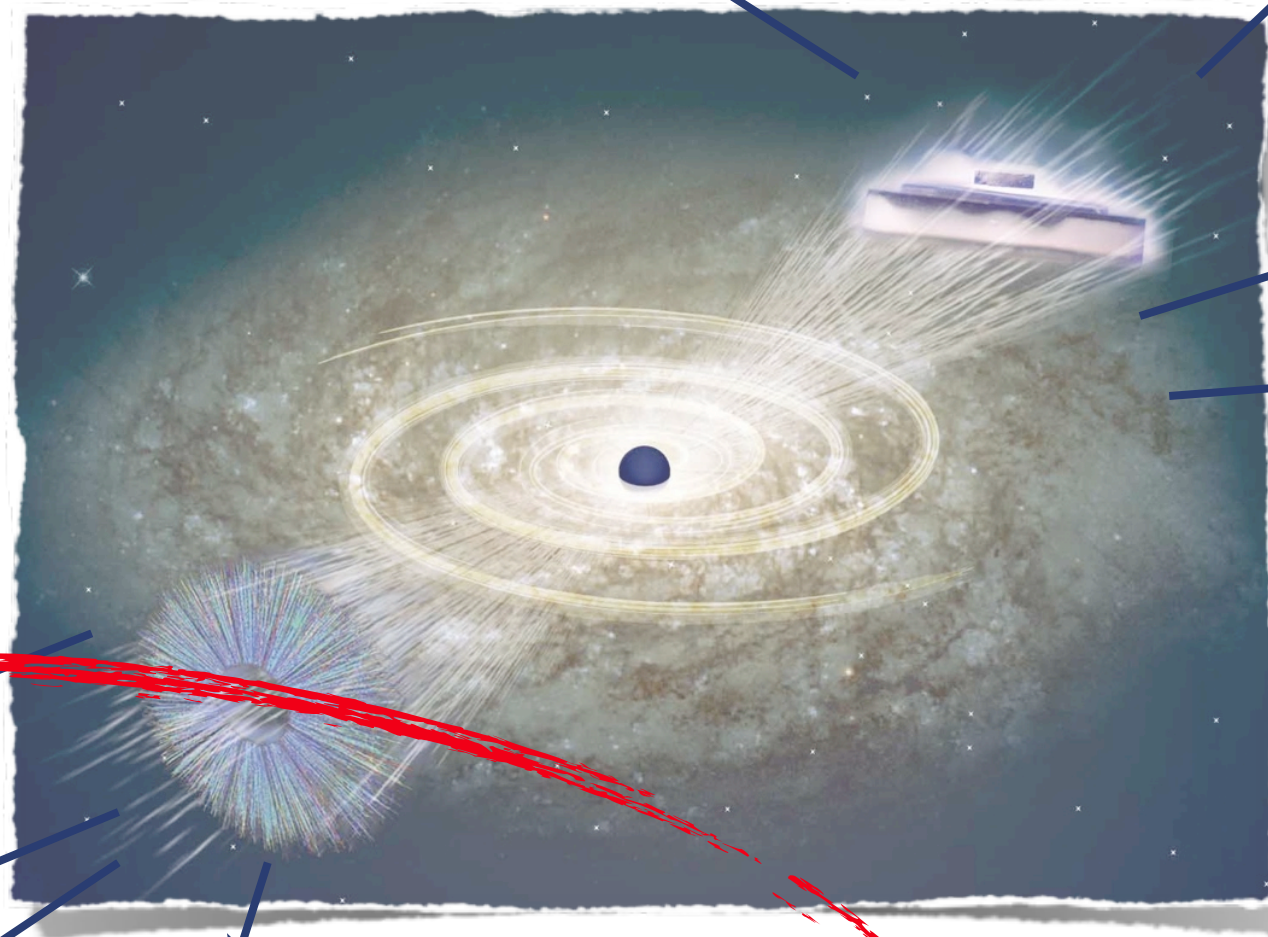
Condensed Matter Physics

Holographic Superconductors

Non-Relativistic AdS/CFT

Non-Fermi liquids  
using gauge/gravity duality

Holographic  
Neutron Stars



Zaananen, 2007

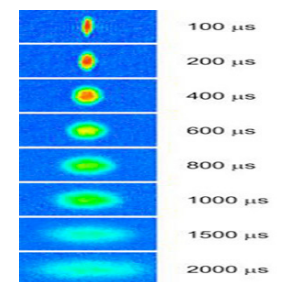
AdS/CFT

AdS/QCD

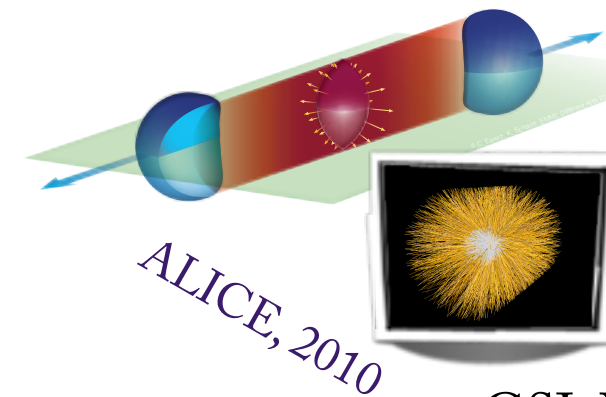
Fluid/Gravity Correspondence

Gauge/Gravity Dualities

High Energy Physics



O'Hara et al., 2002



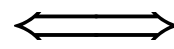
$\eta/s$   
similar

# Gauge/Gravity Duality

$SU(N_c) \mathcal{N} = 4$  SYM

d-dim. **gauge theory**  
(without gravity)

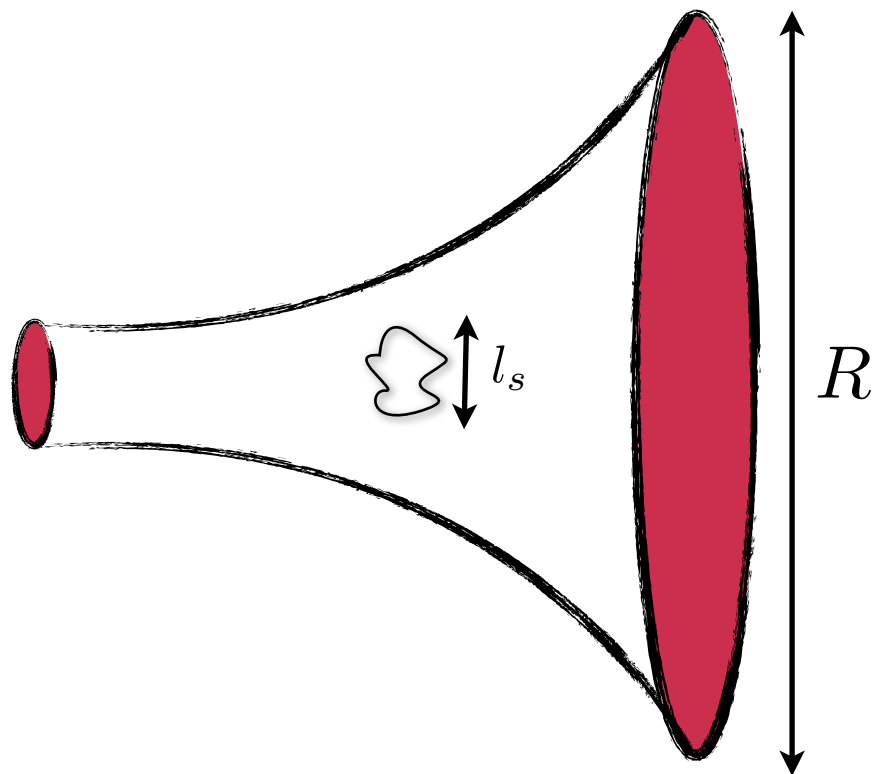
entropy of gauge theory  
 $\propto$  volume



$AdS_5 \times S^5$

d+1-dim. **gravitational theory**

entropy of gravitational theory  
 $\propto$  area



Why is that duality useful?

$$g_{\text{YM}}^2 = 2\pi g_s, \quad R^4 = 4\pi g_s N_c l_s^4, \quad \lambda = g_{\text{YM}}^2 N_c$$

$$\lambda \text{ fixed, } N_c \longrightarrow \infty : \quad g_s \sim \lambda / N_c$$

$$\lambda \longrightarrow \infty : \quad R^4 \sim \lambda l_s^4$$

strongly coupled QFT  $\longleftrightarrow$  weakly coupled gravity

# QCD $\longleftrightarrow$ $\mathcal{N} = 4$ super Yang-Mills

- $\mathcal{N} = 4$  SYM very different from QCD
  - Maximally supersymmetric
  - Conformal theory, coupling is constant
  - No confinement, no chiral symmetry breaking
  - $N_c \rightarrow \infty$  for duality
- At finite  $T$ , differences are smaller:
  - Above  $2T_c$  QCD almost conformal
  - No confinement in QCD above  $T_c$
  - Finite  $T$  breaks supersymmetry

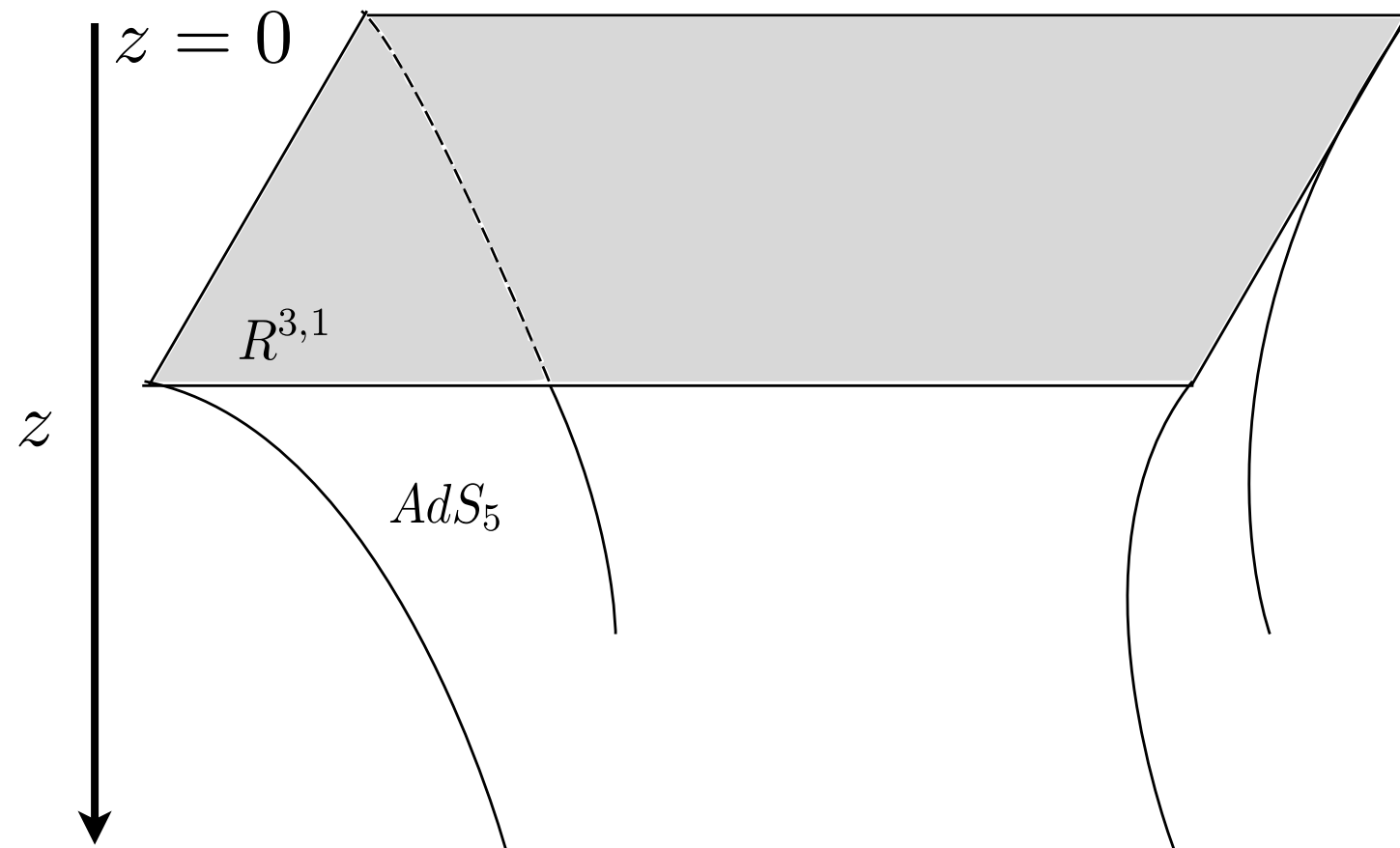
# Basic Properties of AdS

- $AdS_5$  metric:

$$ds^2 = \frac{R^2}{z^2} \left( -dt^2 + d\vec{x}^2 + dz^2 \right) \text{ with } R \text{ being the AdS curvature}$$

- Solution to 5D Einstein-Hilbert action:

$$S = \frac{1}{16\pi G} \int d^5x \sqrt{-g} (\mathcal{R} - 2\Lambda)$$

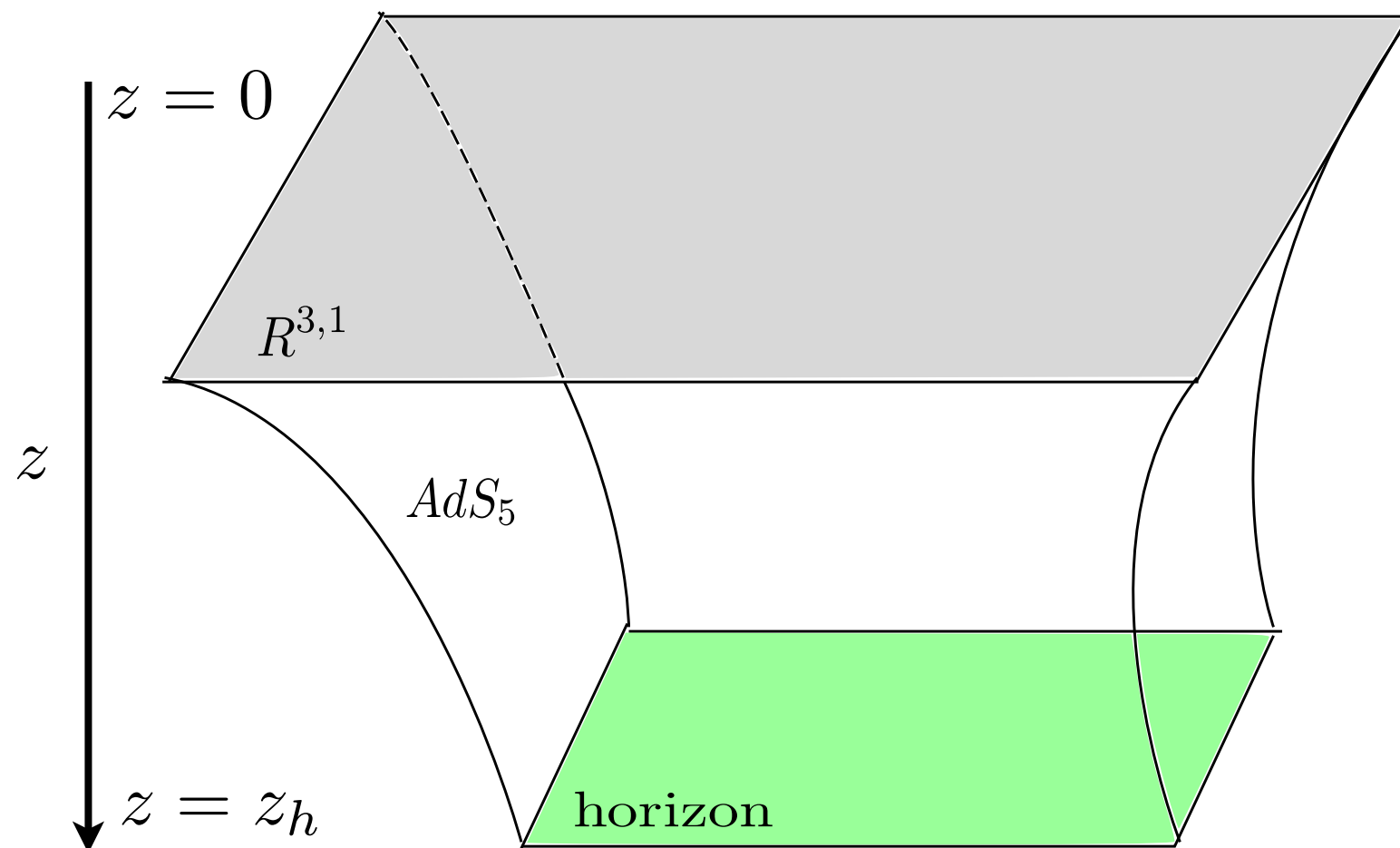


# Basic Properties of AdS

- $AdS_5$  black hole metric:

$$ds^2 = \frac{R^2}{z^2} \left( -h dt^2 + d\vec{x}^2 + \frac{dz^2}{h} \right) \text{ with } h = 1 - \frac{z^4}{z_h^4} \text{ and } T = \frac{1}{\pi z_h}$$

- Solves the same e. o. m.:





# Metric models at finite temperature

- $AdS_5$  BH metric at finite temperature:

$$ds^2 = \frac{R^2}{z^2} \left( -h dt^2 + d\vec{x}^2 + \frac{dz^2}{h} \right) \text{ with } h = 1 - \frac{z^4}{z_h^4} \text{ and } T = \frac{1}{\pi z_h}$$

- $SW_T$  model:

Kajantie, Tahkokallio, Yee

$$ds^2 = \frac{R^2}{z^2} e^{cz^2} \left( -h dt^2 - d\vec{x}^2 - \frac{dz^2}{h} \right)$$

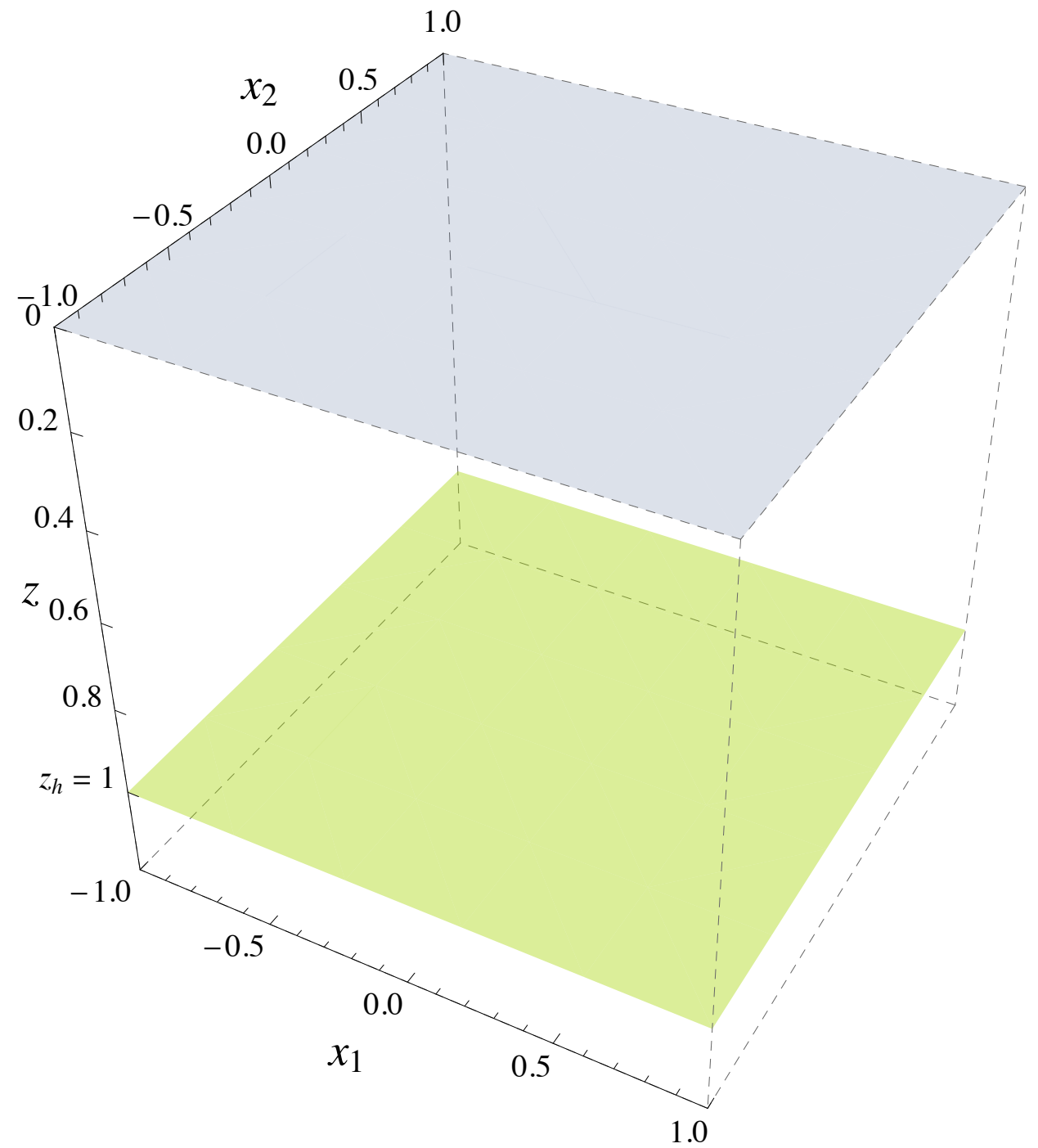
- 2-parameter model:

DeWolfe, Rosen; Gubser

$$ds^2 = e^{2A(\Phi)} \left( -h(\Phi) dt^2 + d\vec{x}^2 \right) + \frac{e^{2B(\Phi)}}{h(\Phi)} d\Phi^2$$

is a solution to equations of motion.

# Screening distance in hot moving plasmas



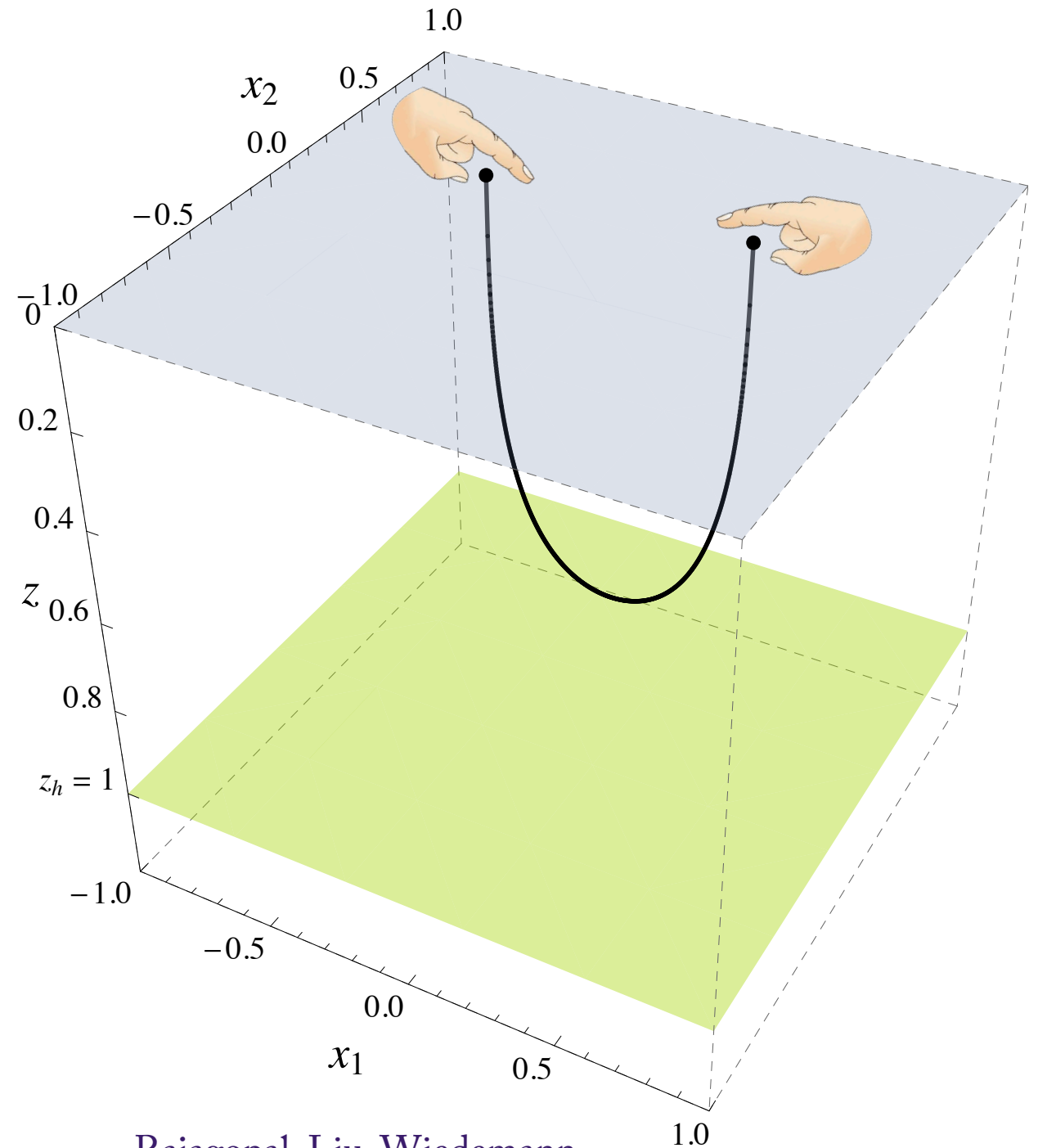
Rajagopal, Liu, Wiedemann

# Screening distance in hot moving plasmas

Nambu-Goto action:

$$S = \frac{1}{2\pi\alpha'} \int d\sigma d\tau \sqrt{-\det g_{\alpha\beta}}$$

with  $g_{\alpha\beta} = G_{\mu\nu} \partial_\alpha x^\mu \partial_\beta x^\nu$



Rajagopal, Liu, Wiedemann

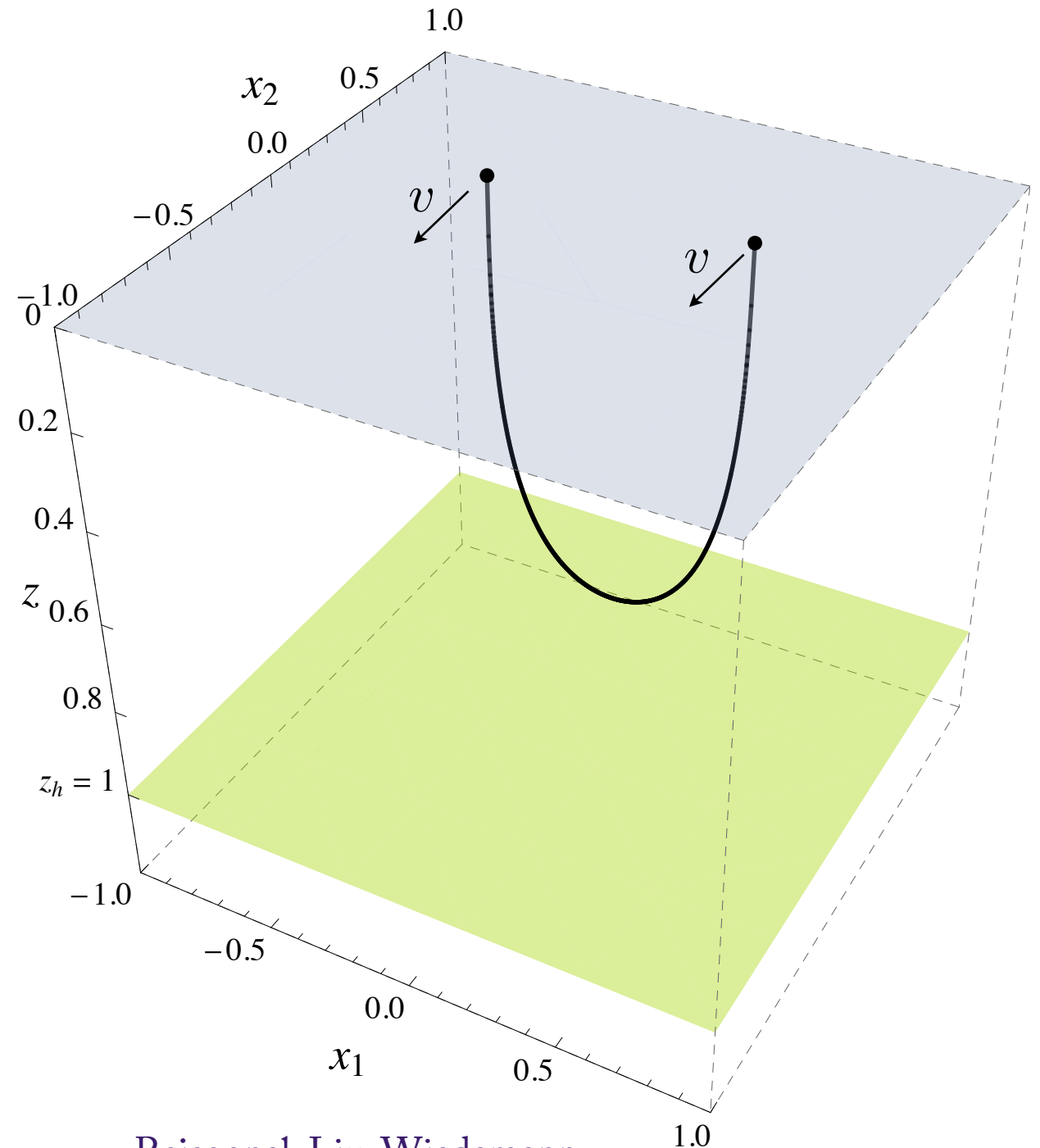
# Screening distance in hot moving plasmas

- Static  $q\bar{q}$ - pair in a hot moving plasma “wind” blowing in  $x_2$ -direction
- velocity  $v = \tanh \eta$
- orientation angle  $\theta$

Nambu-Goto action:

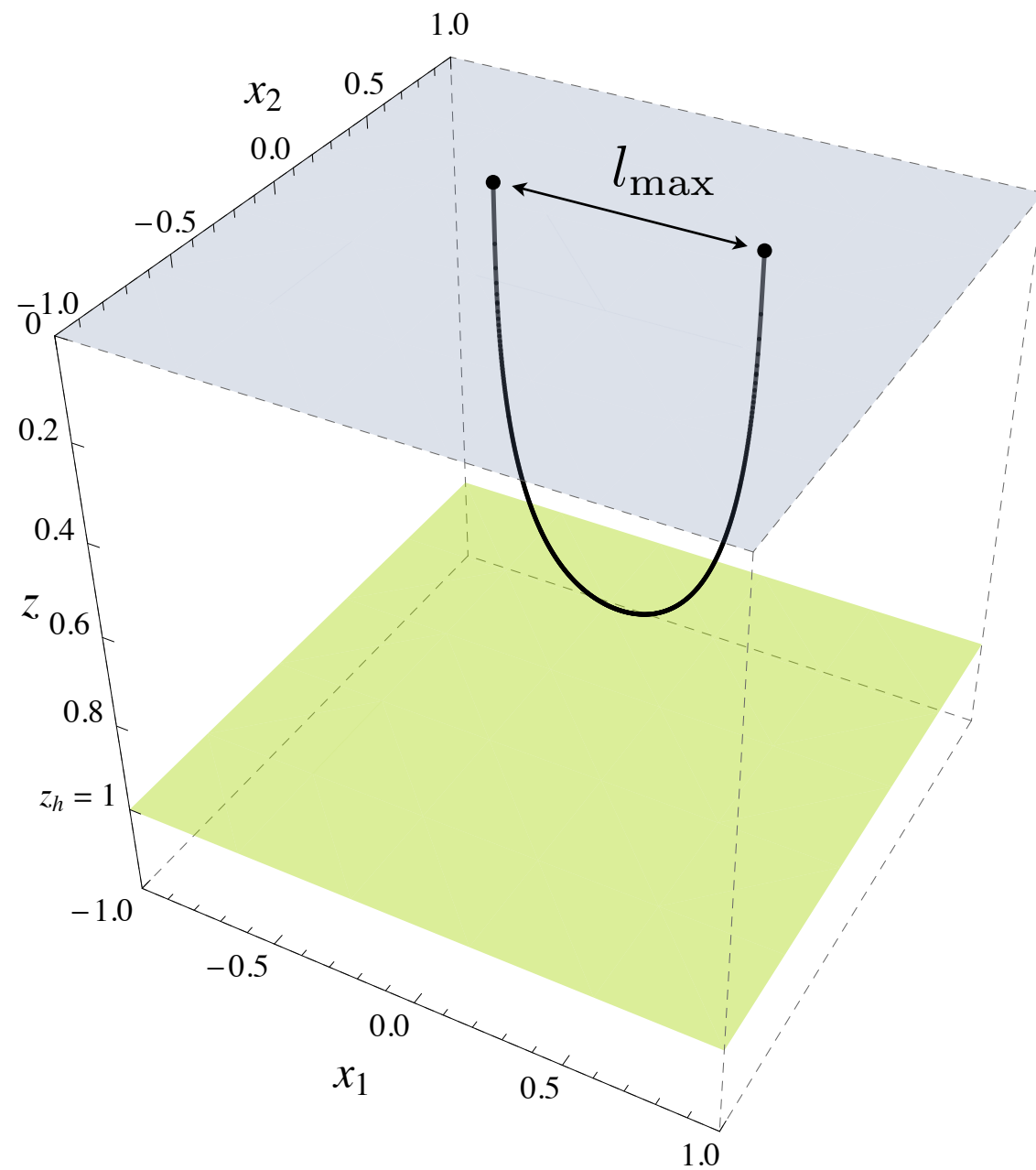
$$S = \frac{1}{2\pi\alpha'} \int d\sigma d\tau \sqrt{-\det g_{\alpha\beta}}$$

with  $g_{\alpha\beta} = G_{\mu\nu} \partial_\alpha x^\mu \partial_\beta x^\nu$



Rajagopal, Liu, Wiedemann

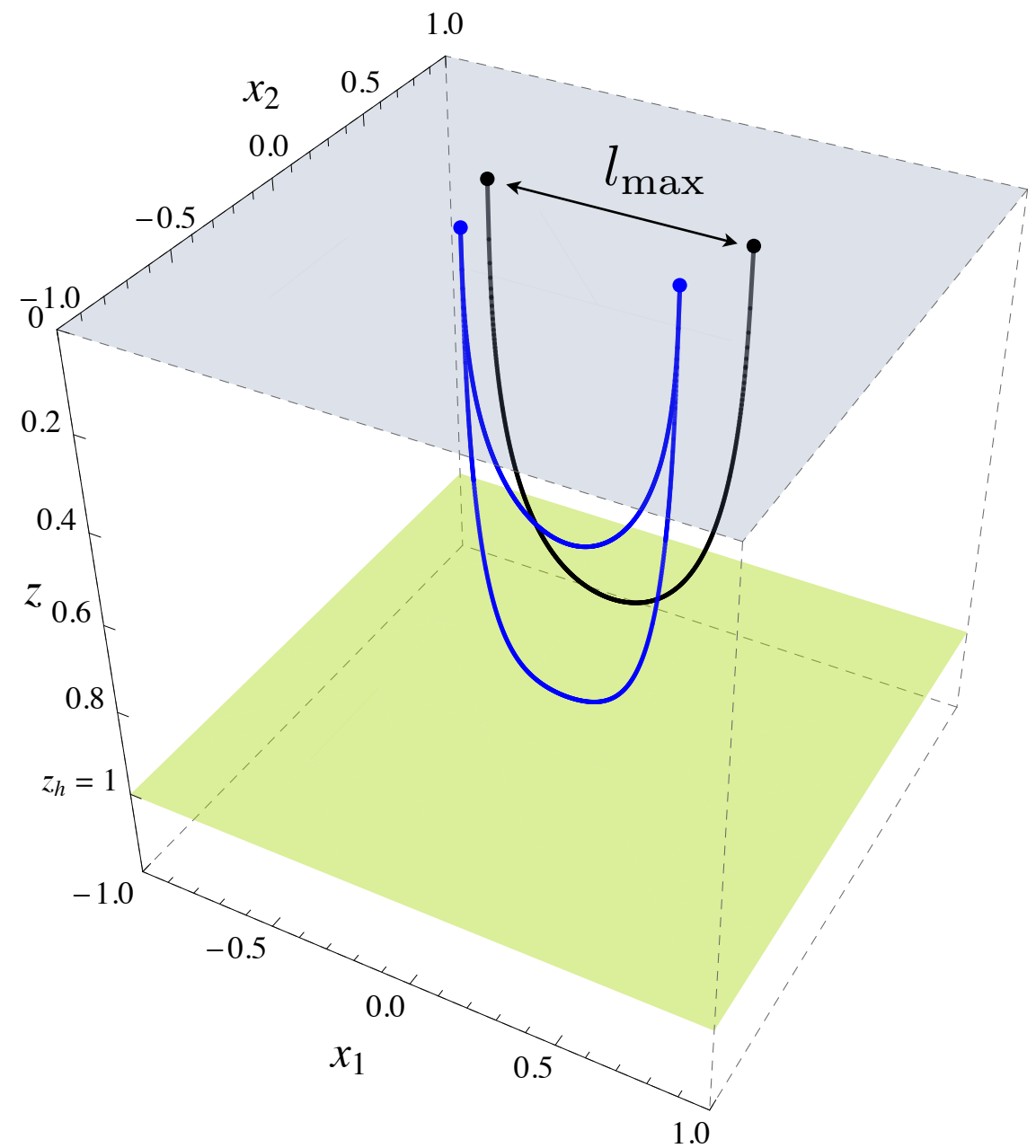
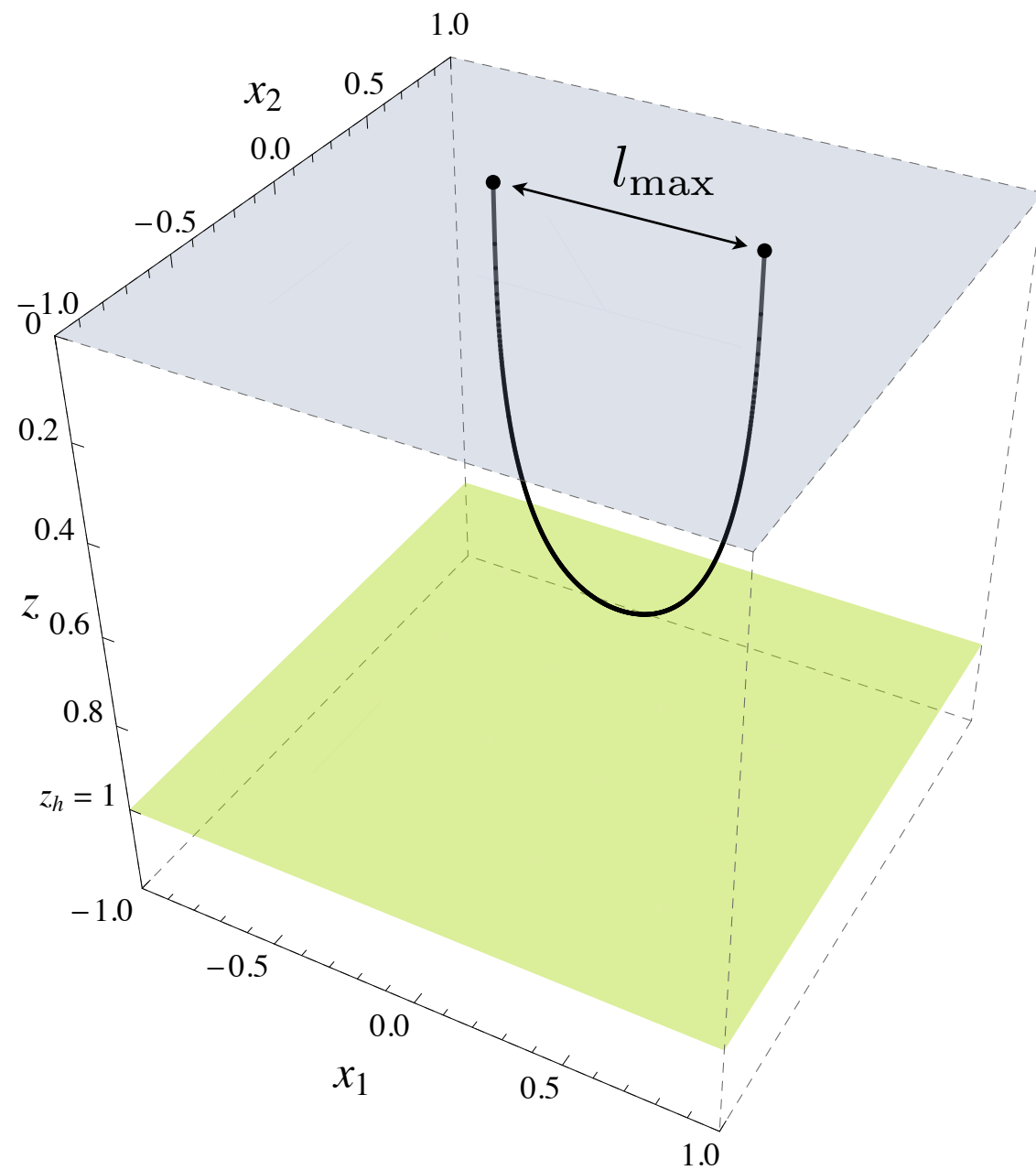
# Configuration of the strings



- The string configuration coming closer to the horizon is unstable.



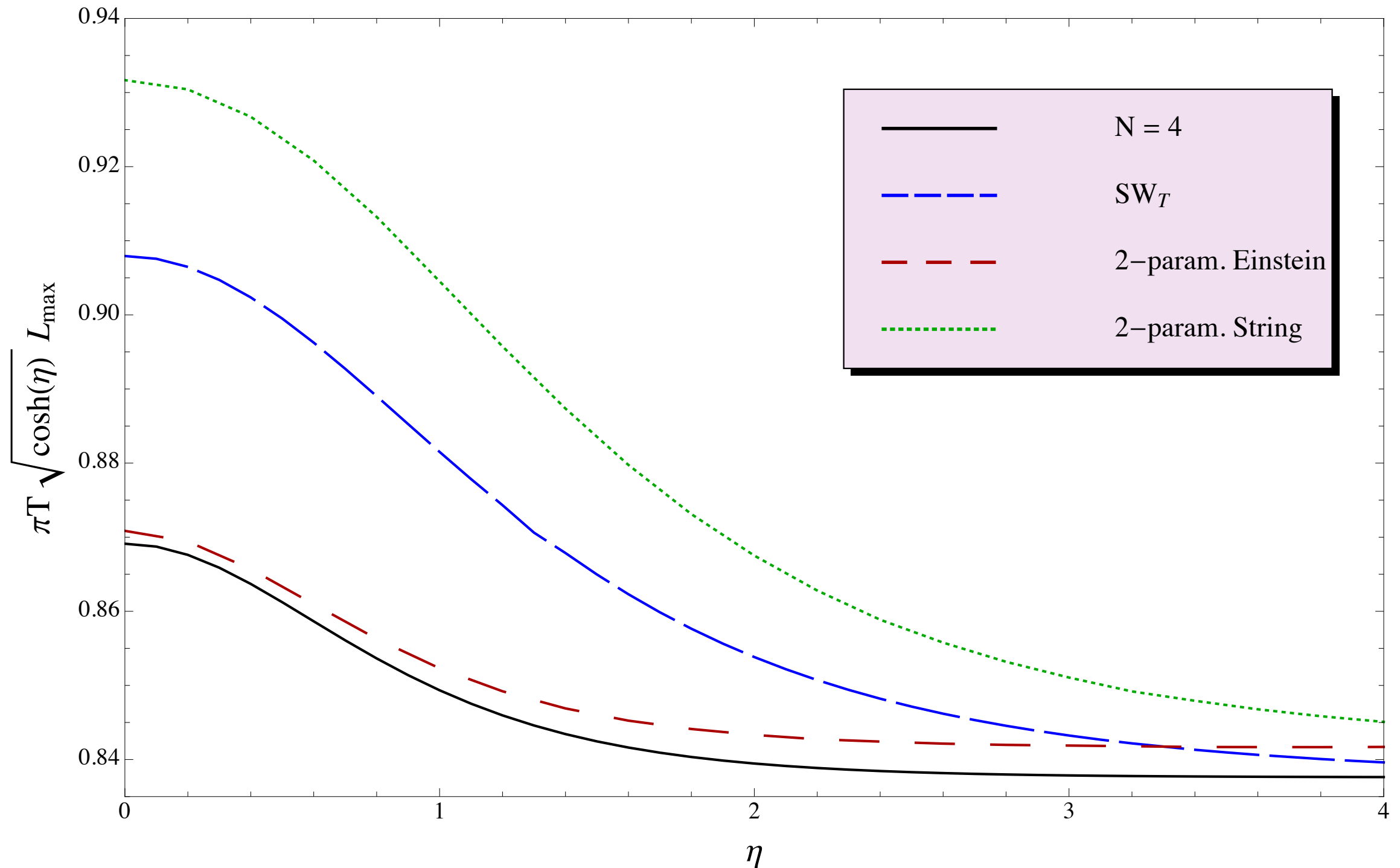
# Configuration of the strings



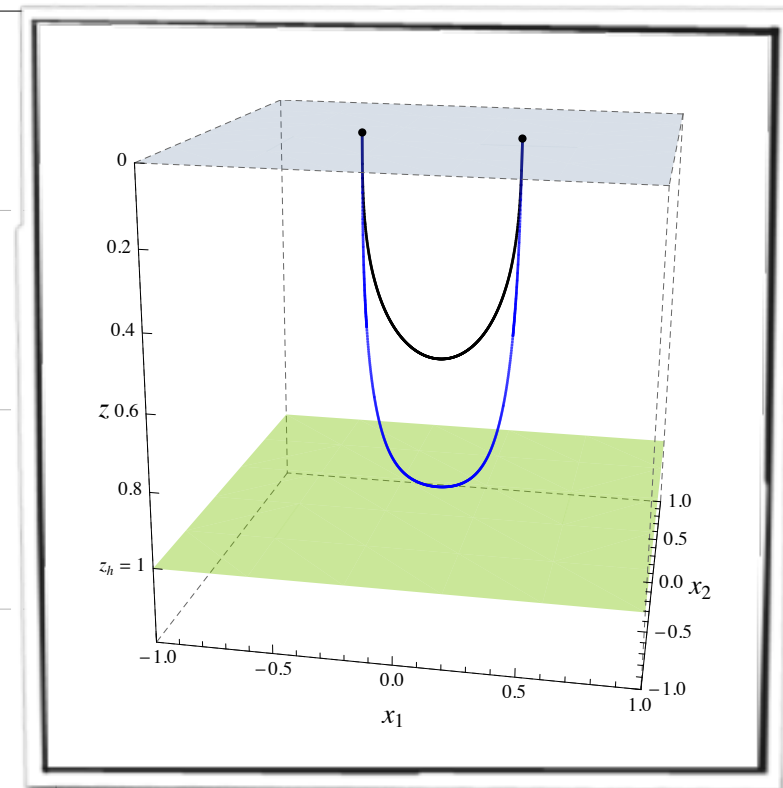
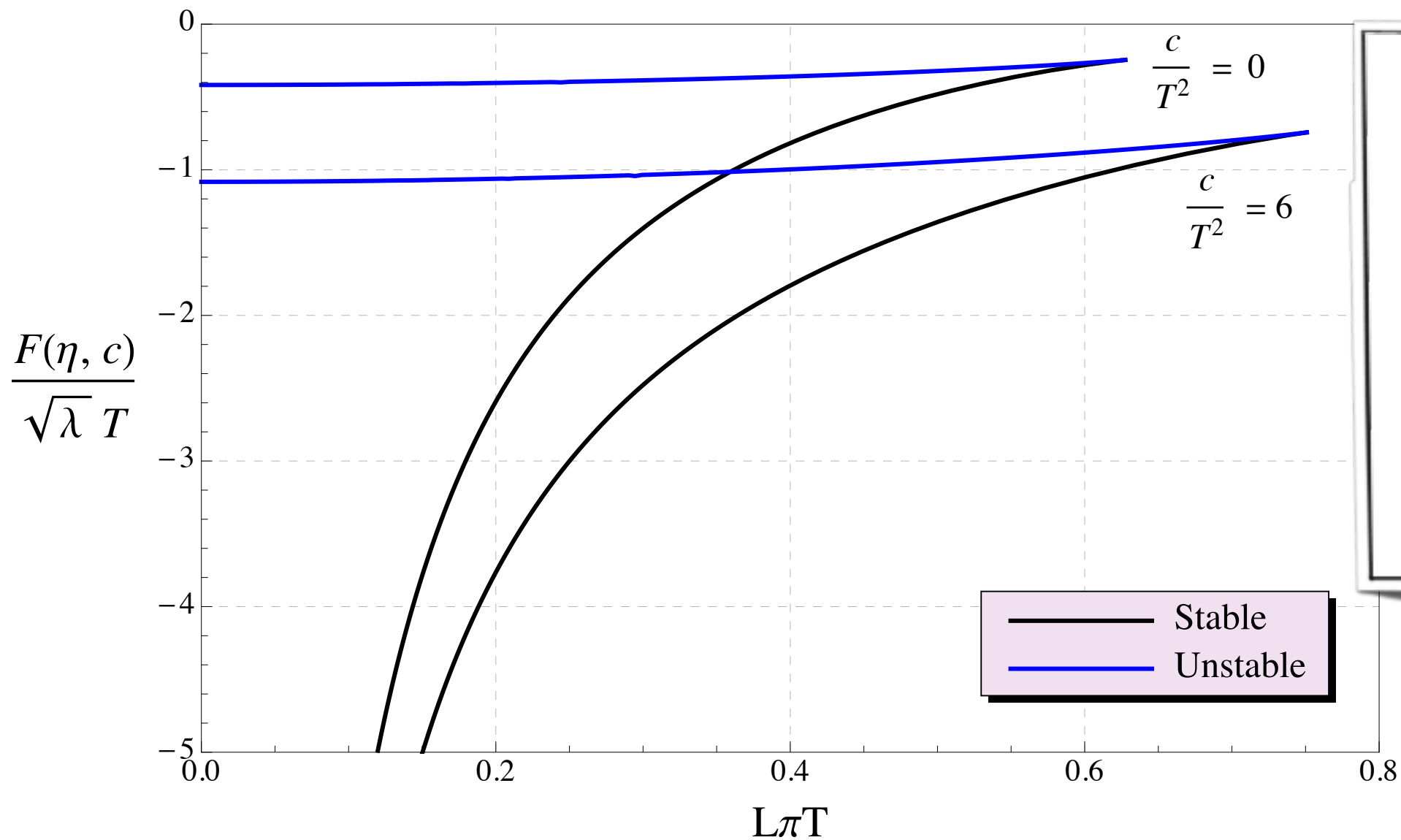
- The string configuration coming closer to the horizon is unstable.

# Screening distance bound

■  $L_{\max}$  is minimal for  $\mathcal{N} = 4$ .

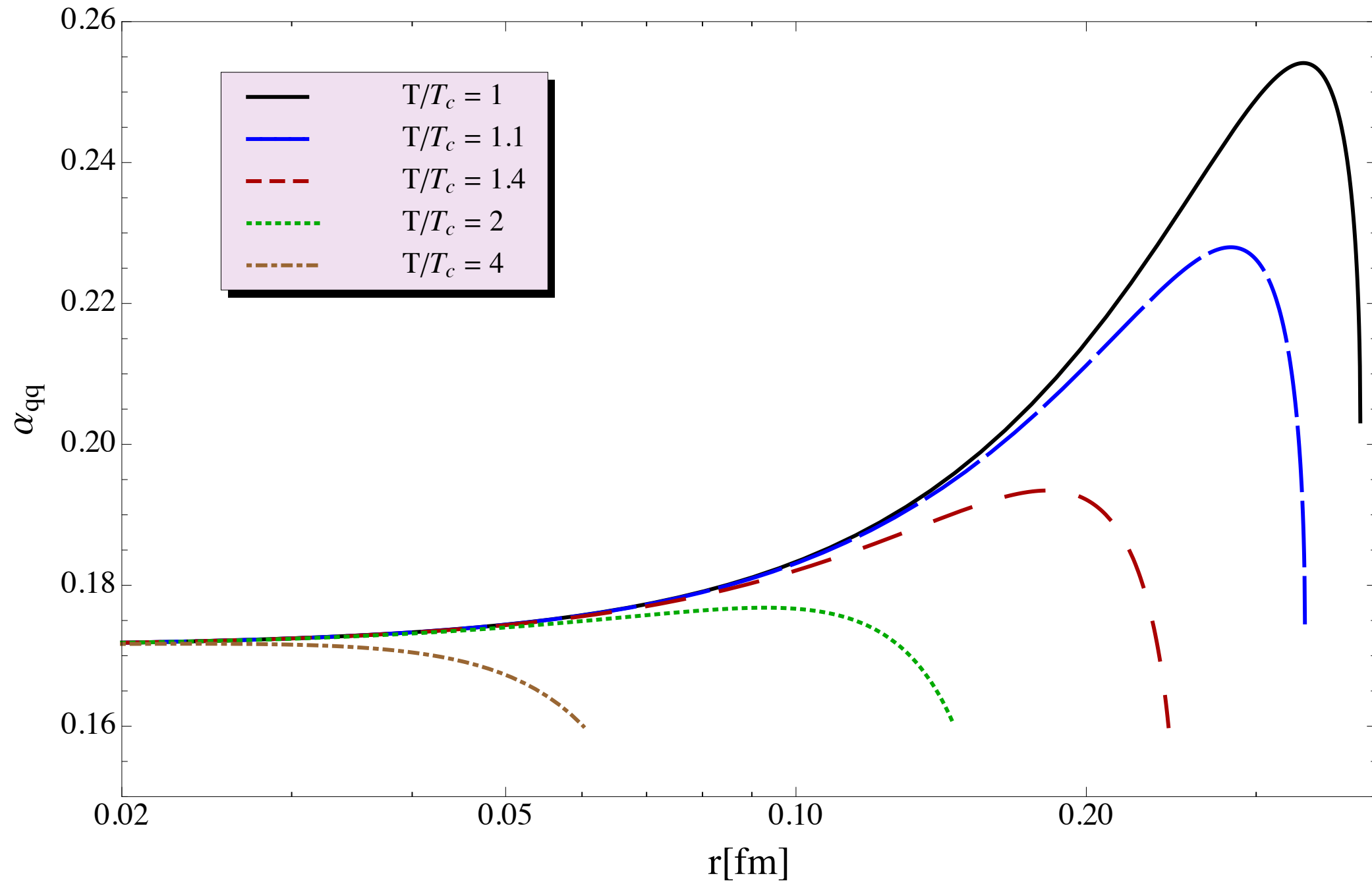


# $Q\bar{Q}$ -free energy: results



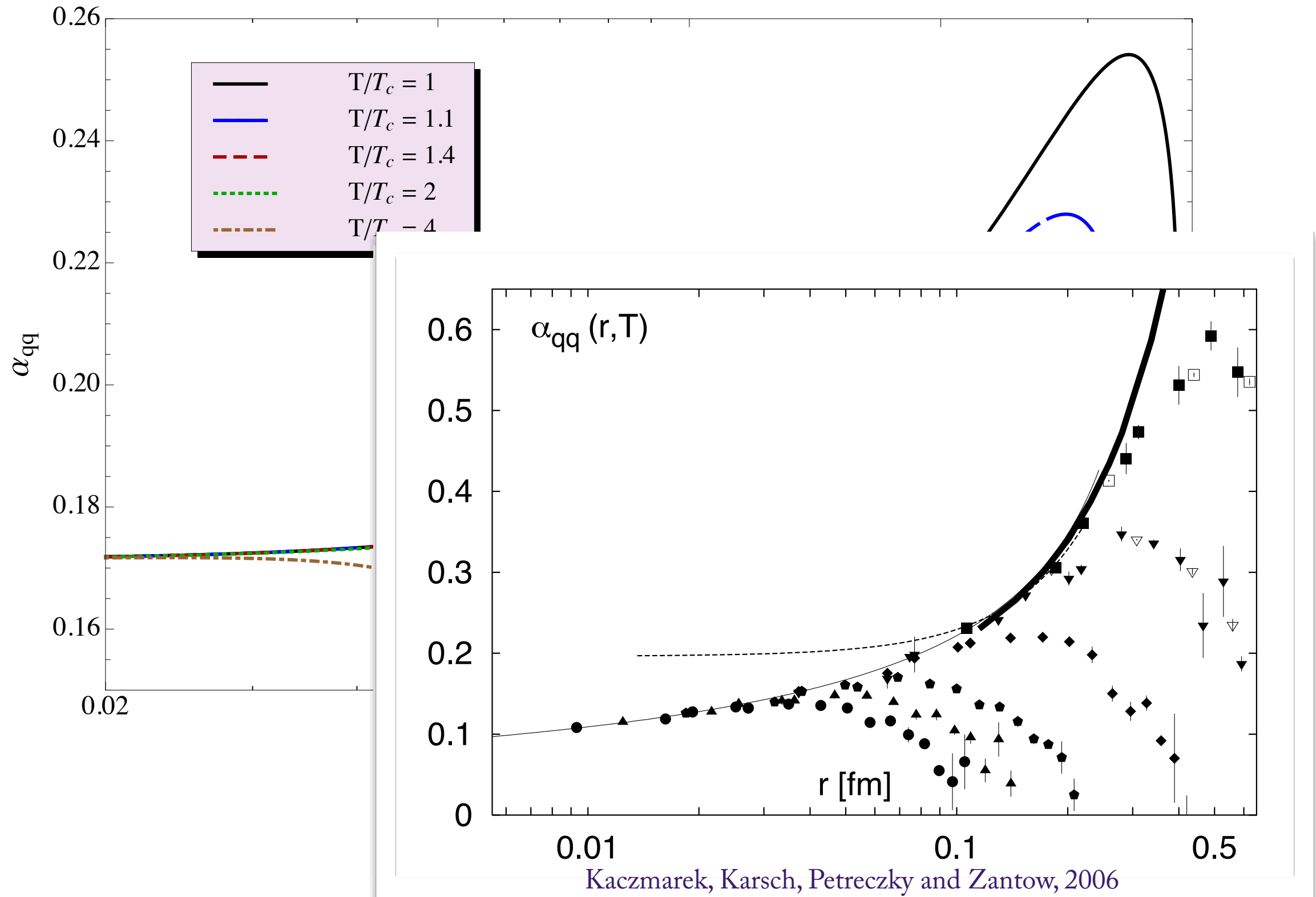
- Free energy of  $q\bar{q}$ -pair at finite rapidity  $\eta = 1$ .
- Unstable configurations are weaker bounded.

# Running Coupling from Free Energy



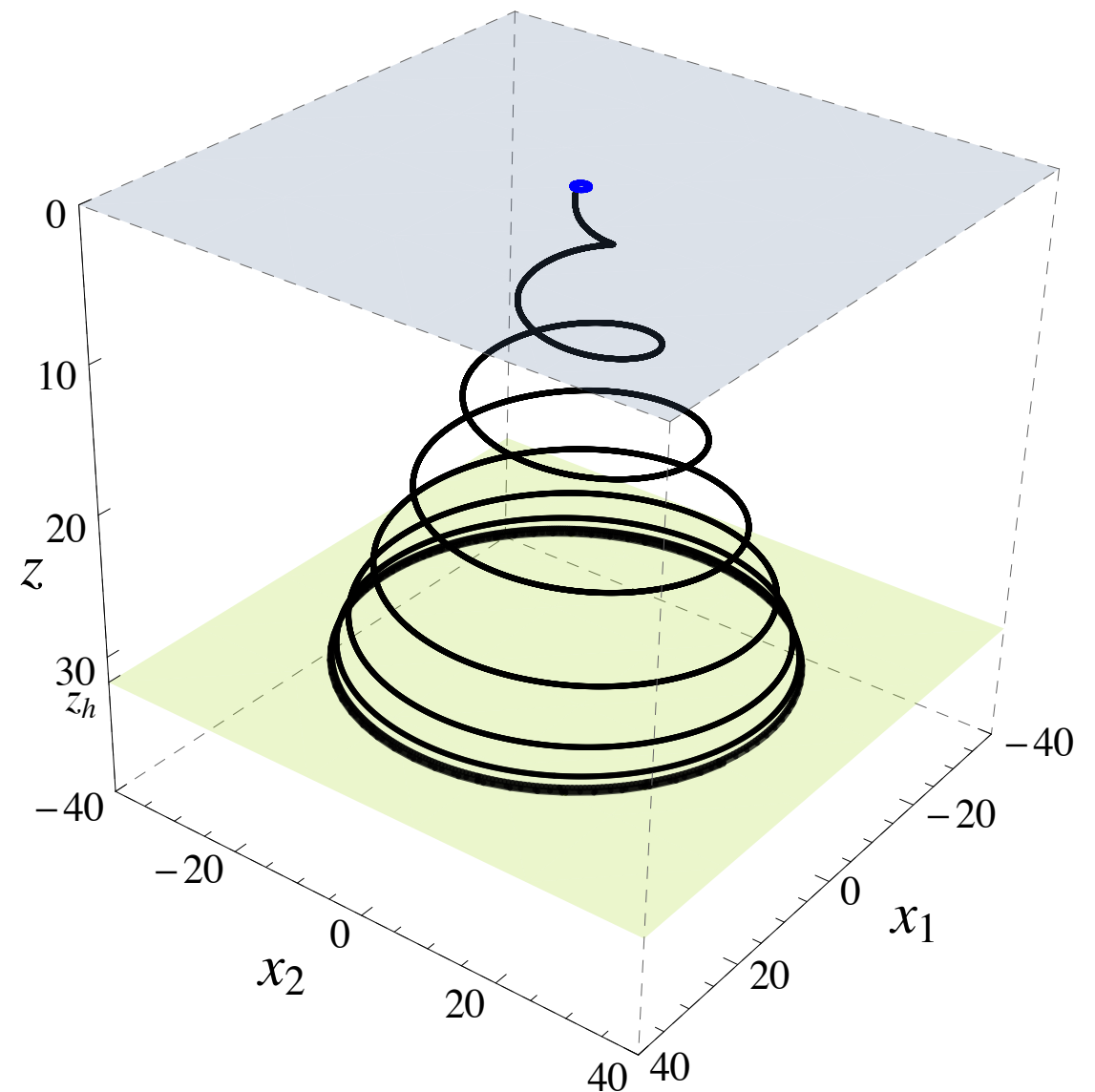
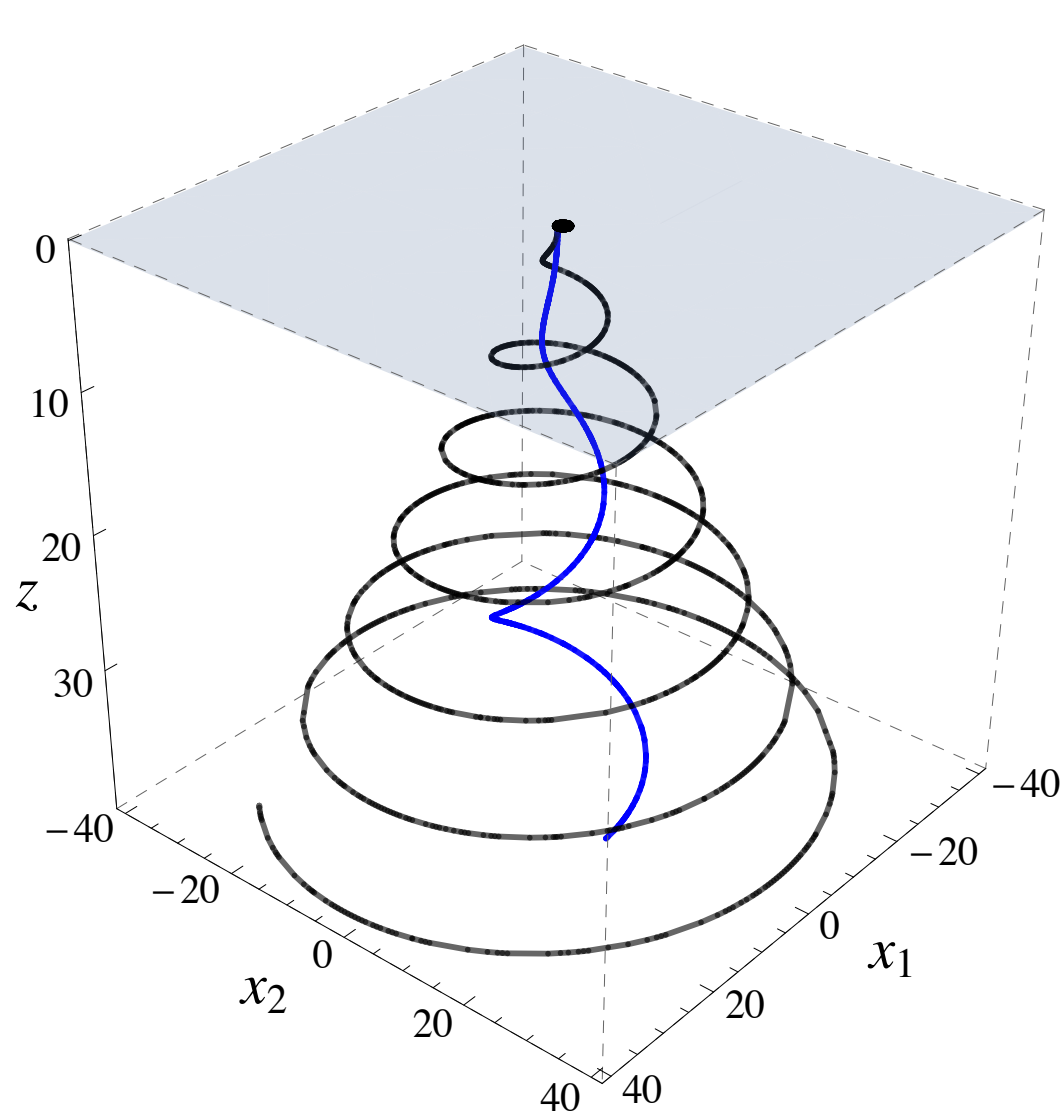
- Coupling  $\alpha_{qq}$  is defined as  $\alpha_{qq} = \frac{3r^2}{4} \frac{dF(r, T)}{dr}$  in QCD.
- Many possibilities by rescaling the parameters.

# Running Coupling from Free Energy





# Rotating Quark at Finite Temperature



- Is energy loss due to synchrotron radiation or due to drag dominant?
- What happens in deformed models?
  - $dE/dt$  is very *robust*.

# Rotating Quark in Deformed Metric Models

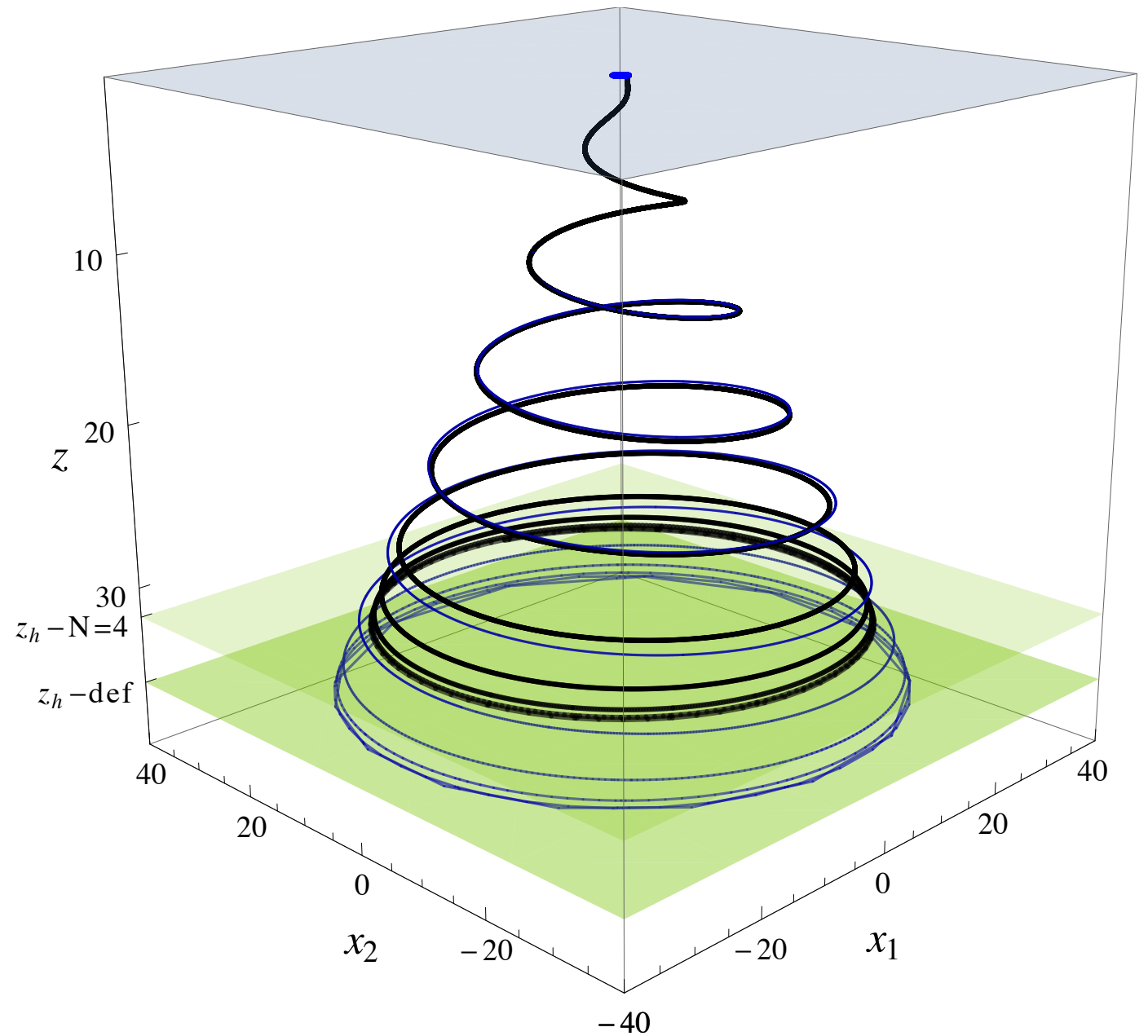
- Is  $\omega \ll \pi T$ ,  $R_0 \ll 1/\omega$

$$\text{then } \left. \frac{dE}{dt} \right|_{\text{RotQ}} \approx \left. \frac{dE}{dt} \right|_{\text{Drag}}$$

- Is  $\omega \gg \pi T$ ,  $R_0 \omega = v \approx 1$

$$\text{then } \left. \frac{dE}{dt} \right|_{\text{RotQ}} \approx \left. \frac{dE}{dt} \right|_{\text{VacRad}}$$

*Vacuum radiation of conformal  $\mathcal{N} = 4$*



$$T = 0.01, \omega = 0.7, R_0 = 1, \phi = \phi_{\max}$$

- Vacuum radiation is independent of the deformation  $\phi$ .
- Universal scaling in the crossover regime.

# Conclusions

- Although being a conjecture the AdS/CFT correspondence as a realisation of the *Holographic principle* is a very powerful tool for qualitative and quantitative analysis, e.g.:
  - *Robustness* and *Universality* of the screening distance.
  - Running coupling of  $q\bar{q}$  - pairs resembles Lattice QCD data.
  - *Robustness* of the energy loss of rotating quarks in deformed models.
- Many other more sophisticated models (e.g. including D3/D7 branes) available that nicely reproduce many QCD features.

Thank you for your  
attention!

# Rotating Quark in Deformed Metric Models

■ Is

the

$$\frac{\left. \frac{dE}{dt} \right|_{\text{RotQ}}}{\left. \frac{dE}{dt} \right|_{\text{Drag}}} \rightarrow \frac{\Pi \omega z_*^2}{v^2}$$

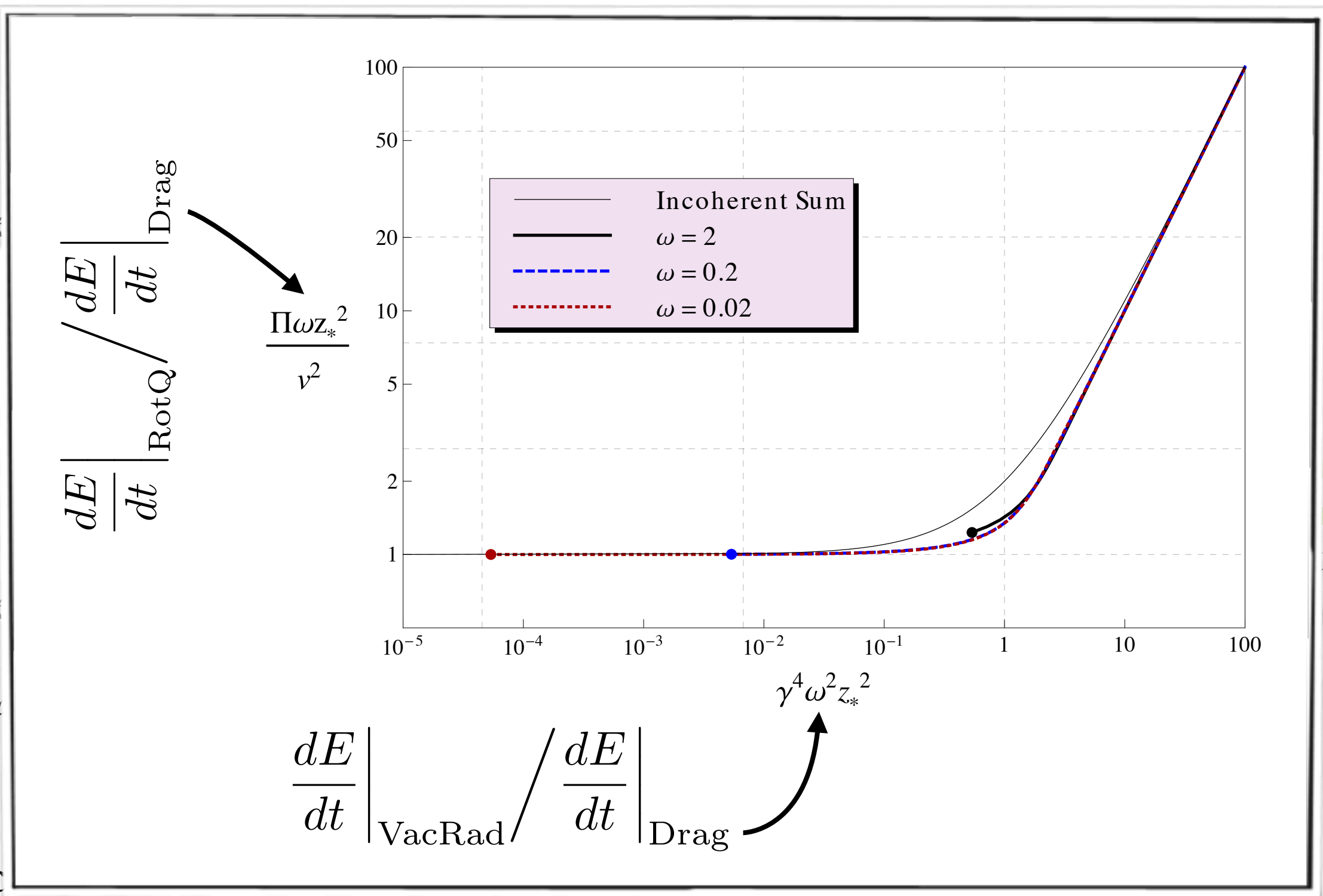
■ Is

the

Vac

$$\frac{\left. \frac{dE}{dt} \right|_{\text{VacRad}}}{\left. \frac{dE}{dt} \right|_{\text{Drag}}} \rightarrow \gamma^4 \omega^2 z_*^2$$

■ Vac



■ Universal scaling in the crossover regime.