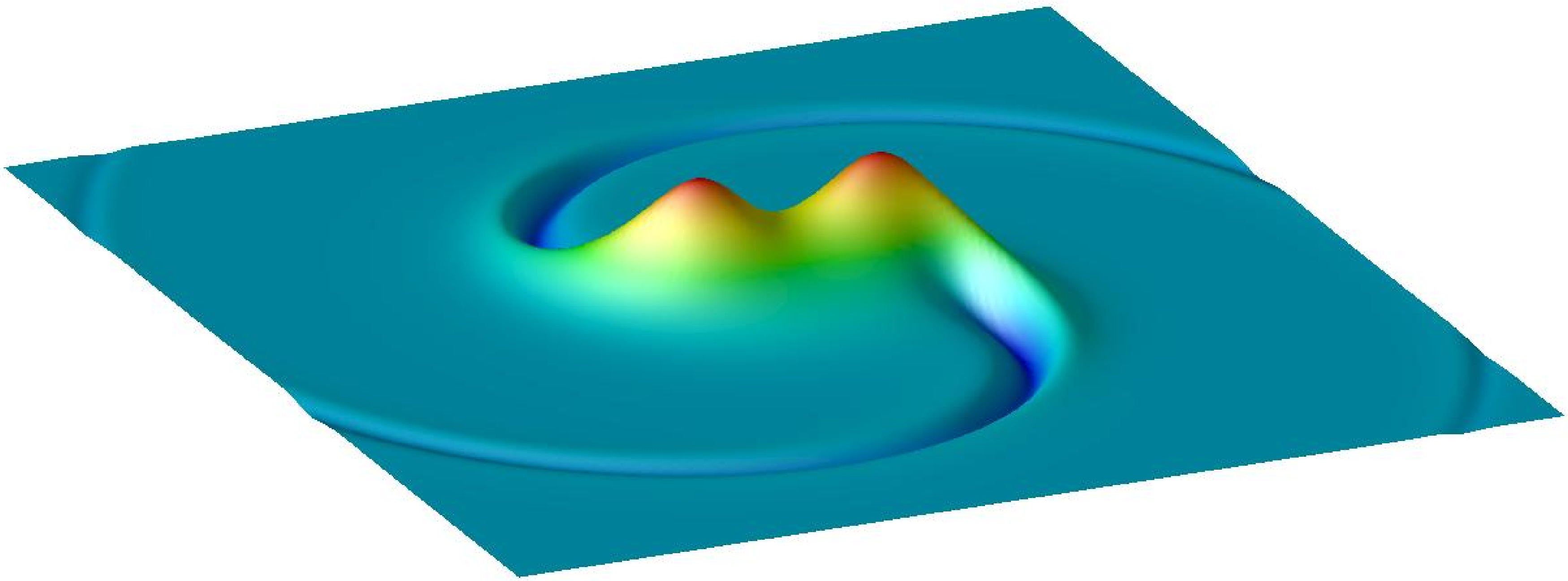
Holographic Theories with Fundamental Matter



with Rowan Thomson & David Mateos;
Peter Langfelder & Andrei Starinets

Outline:

1. Introductory remarks

2. Gauge/Gravity duality with fundamental fields

   → add probe branes

3. Probe branes in thermal backgrounds

   → first-order phase transition

Mateos, RCM + Thomson (hep-th/0605046)

Aharony, Sonnenschein & Yankielowicz (hep-th/0604161)
Albash, Filev, Johnson & Kundu (hep-th/0605088; hep-th/0605175)
Karch & O'Bannon (hep-th/0605120)
Peeters, Sonnenschein & Zamaklar (hep-th/0606195)

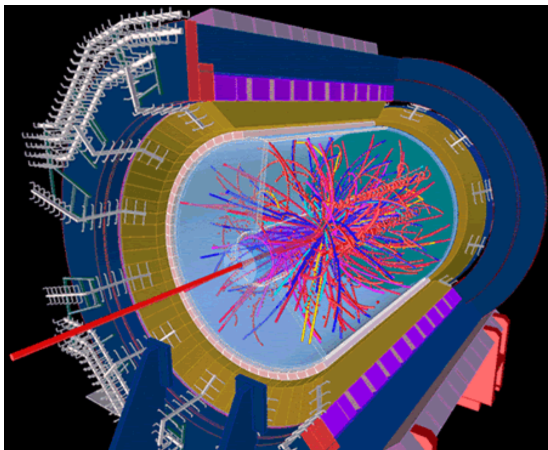
4. Transport properties of plasma

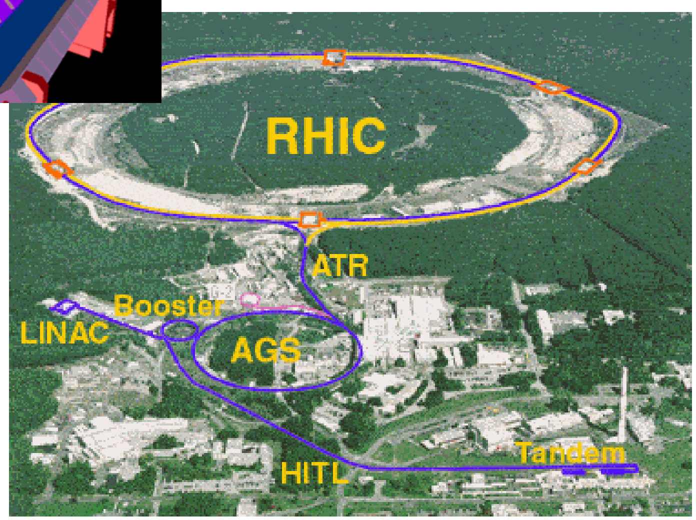
   → diffusivity, viscosity, ...

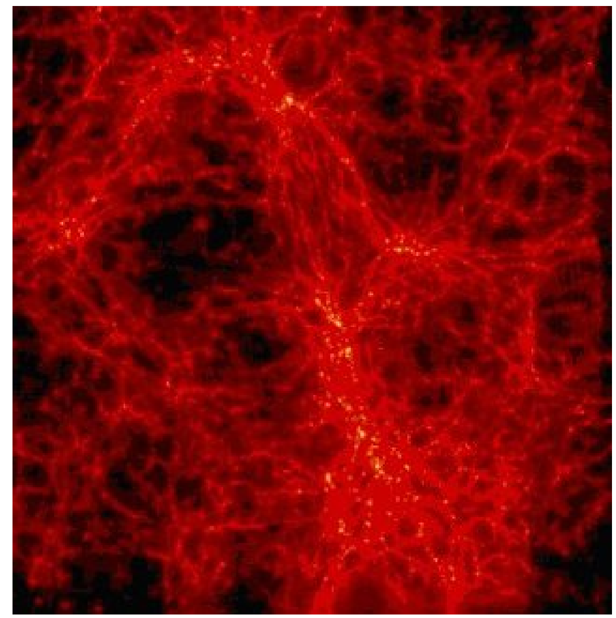
5. Conclusions/Outlook

Behaviour (e.g., real-time dynamics) of strongly-coupled QCD plasma is of interest for RHIC and early universe cosmology

Theoretical tools to study such strongly-coupled systems are very limited (e.g., nonexistent)







Behaviour (i.e., real-time dynamics) of strongly-coupled QCD plasma is of interest for RHIC and early universe cosmology

Theoretical tools to study such strongly-coupled systems are very limited (i.e., nonexistent)

Gauge/gravity duality provides simple tools to study some strongly-coupled guage theories, e.g.,

Type IIb ~~strings~~ sugra
on $AdS_5 \times S^5$
with RR flux N_C

⟷

D=4 N=4 $U(N_C)$
super-Yang-Mills

limited to: large N_C and large 't Hooft coupling

	QCD	**N=4 SYM**
T=0	confinement, discrete spectrum, scattering, ...	conformal, continuous spectrum, no S-matrix, SUSY, ...

very different !!

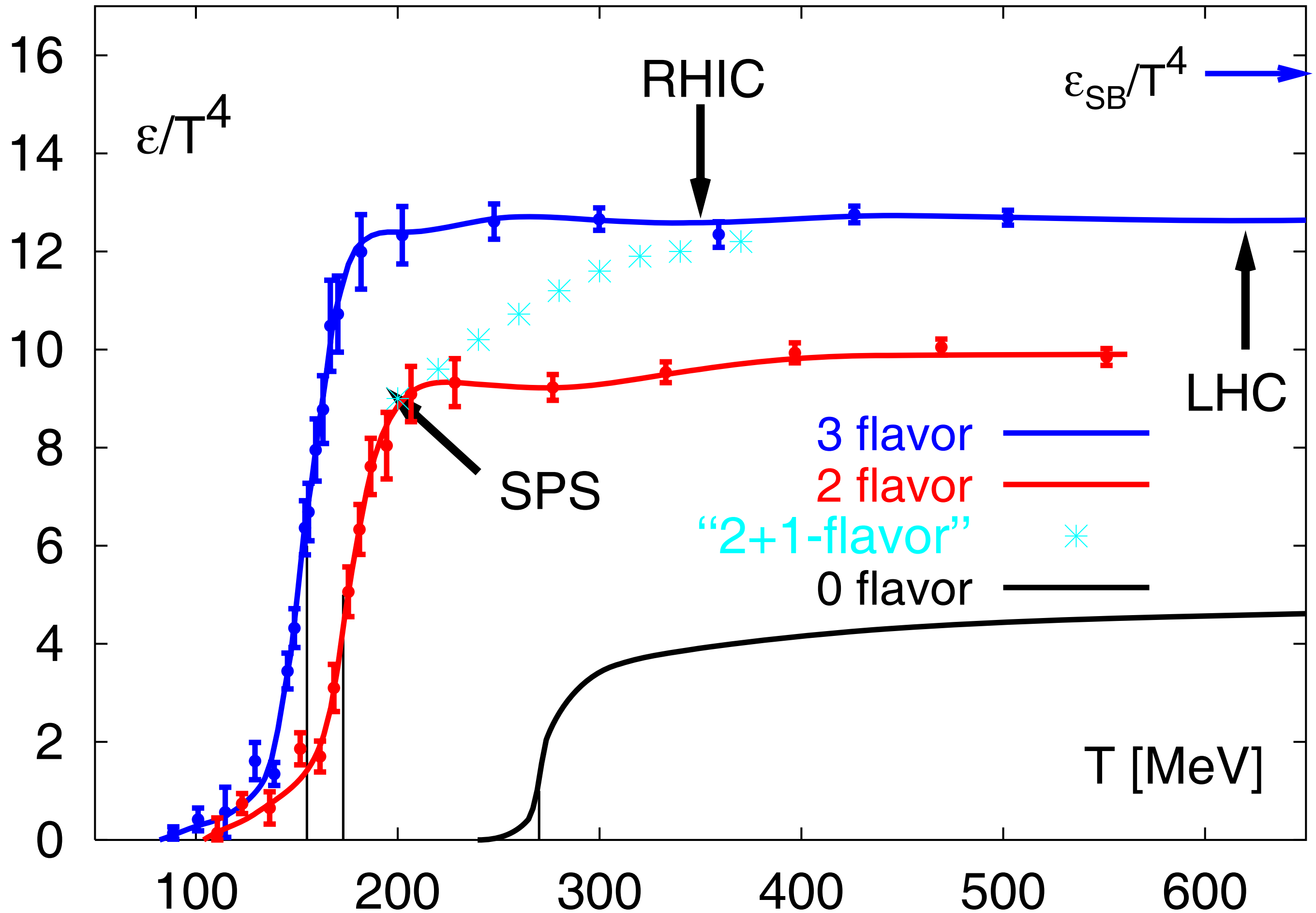
$T>T_c$	strongly-coupled plasma of gluons & adjoint matter deconfined, screening, finite corr. lengths, . . .	strongly-coupled plasma of gluons & fundamental matter deconfined, screening, finite corr. lengths, . . .

very similar !!

$T>>T_c$	runs to weak coupling	remains strongly-coupled

very different !!

“The matter matters!”



[lattice results reviewed in: nucl-th/0405013]

N=4 U(N_C) super-Yang-Mills contains only adjoint fields!

(Karch and Katz)

Fundamental fields:

Decoupling limit of N_c D3-branes with N_f D7-branes

Low-energy limit with $\alpha' E^2, L^2/\alpha' \to 0$

Field theory:

U(N_c) super-Yang-Mills ← U(N_c) adjoint

coupled to N_f massive hypermultiplets ← fund. in U(N_c) & global U(N_f)

(SUSY: $\mathcal{N}=4 \to \mathcal{N}=2$)

Gravity theory:

$AdS_5 \times S^5$ with N_C units of RR flux

containing N_f D7 probe branes

Gauge/gravity dictionary:

supergravity modes: $h_{\mu\nu} \quad \leftrightarrow \quad T_{\mu\nu}$

D7-brane modes:

$$A_\mu^{ij} \;\leftrightarrow\; J_\mu^{ij} \simeq \mathrm{Tr}\left[\bar{\psi}^i \gamma_\mu \psi^j + \Phi^i D_\mu \Phi^j\right]$$

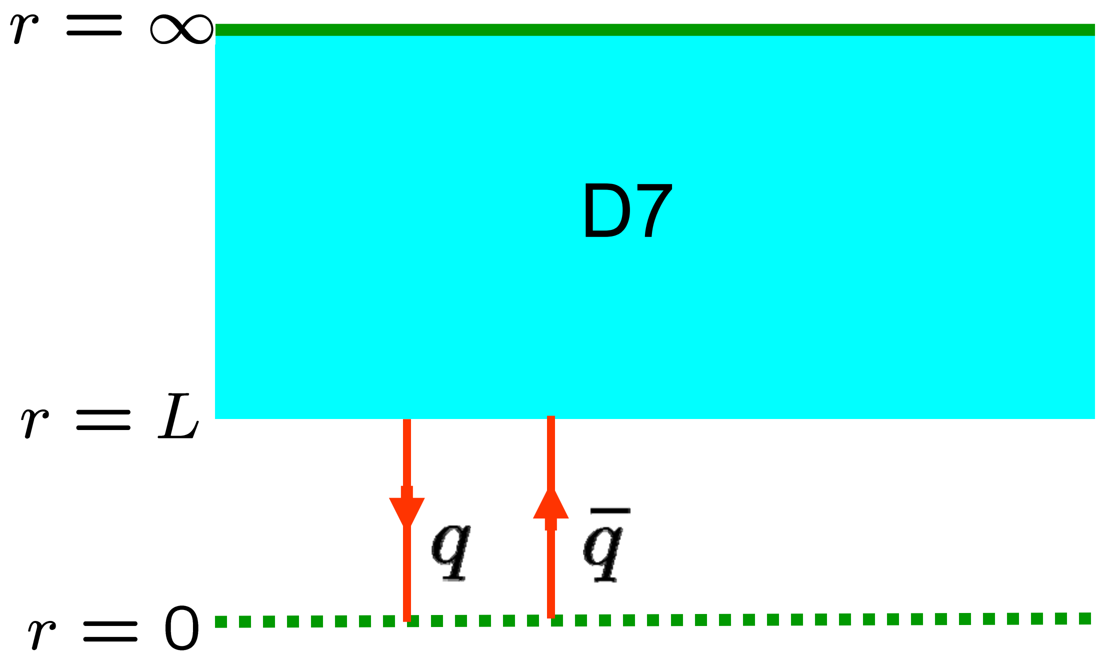
Probe approximation: $N_f / N_c \to 0$

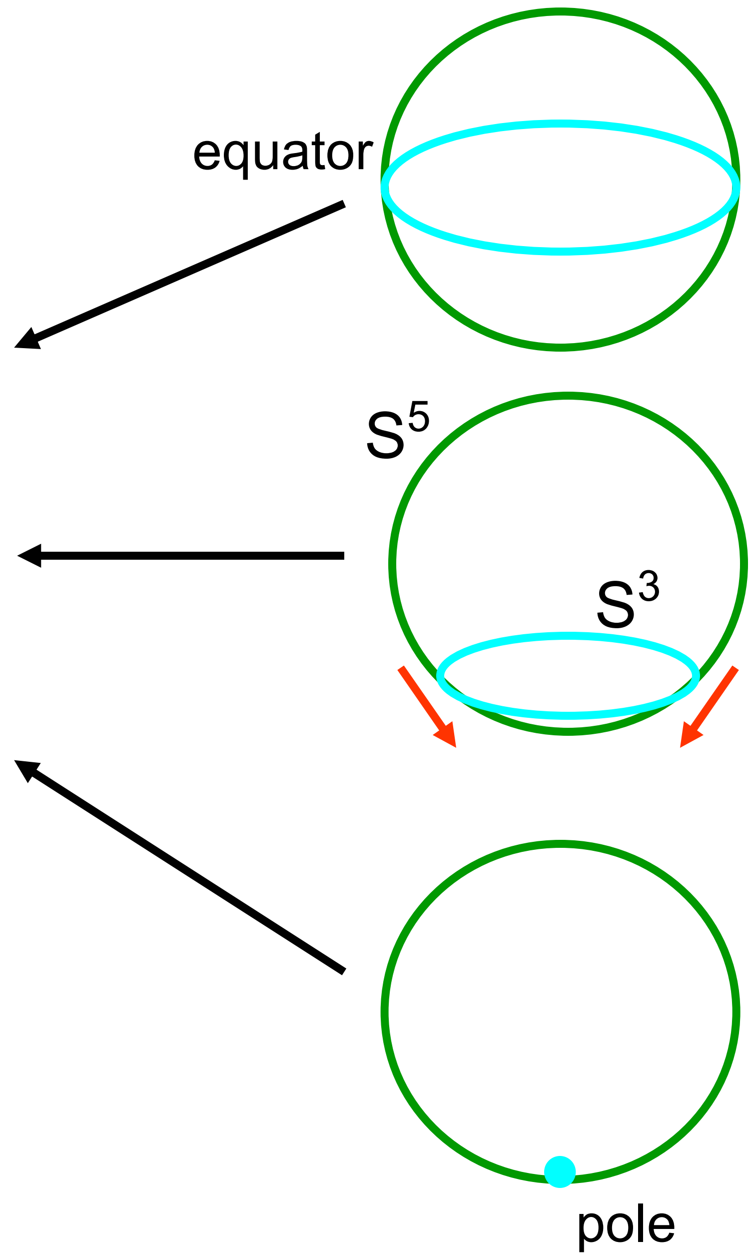
The above construction does not take into account the "gravitational" back-reaction of the D7-branes!

$\to$ considering large-N_c limit with N_f fixed

(see, however: Burrington et al; Kirsch & Vaman; Casero, Nunez & Paredes)

Geometry:

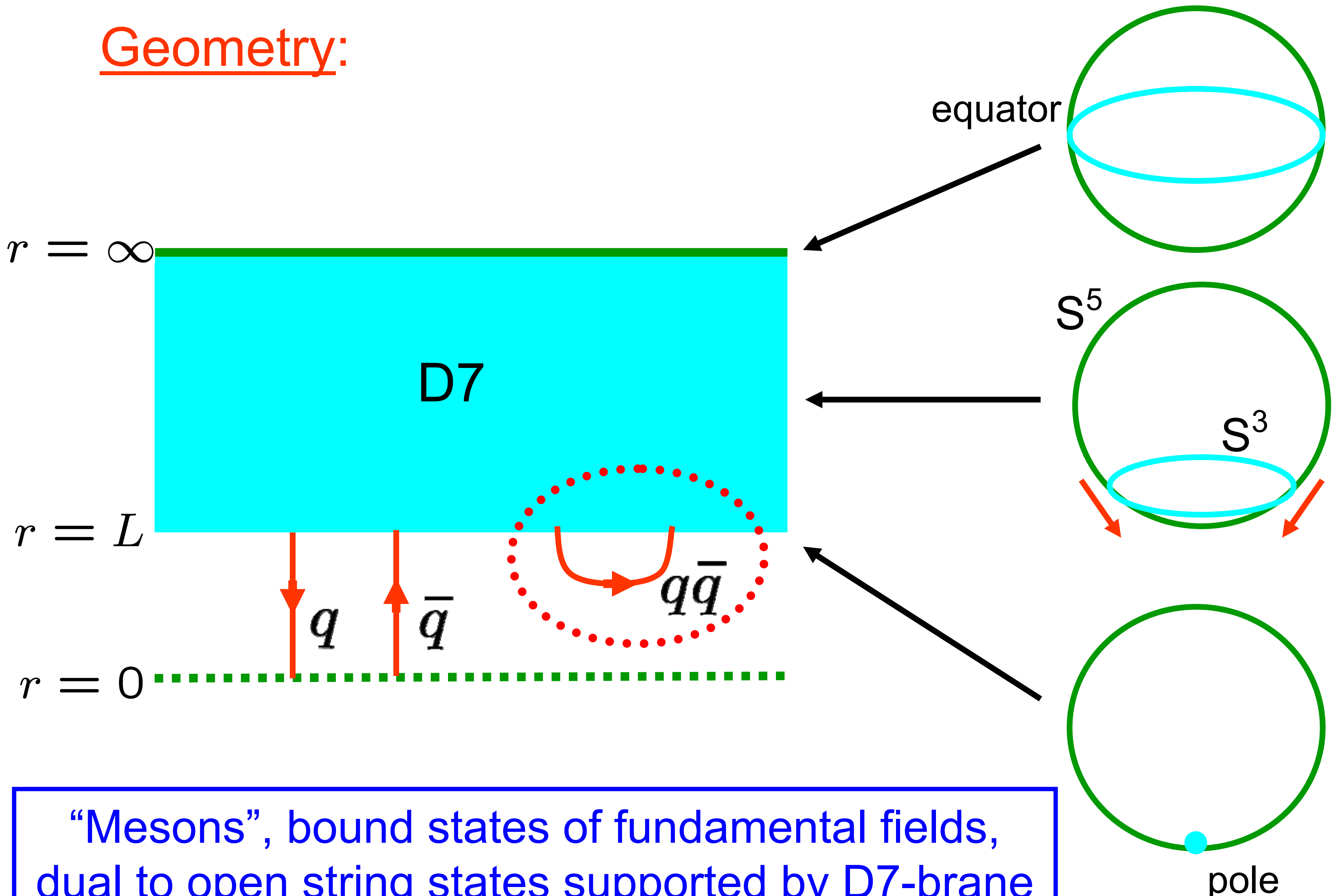




Free quarks appear with mass:

$$m_q = \frac{L}{2\pi\alpha'}$$

Geometry:



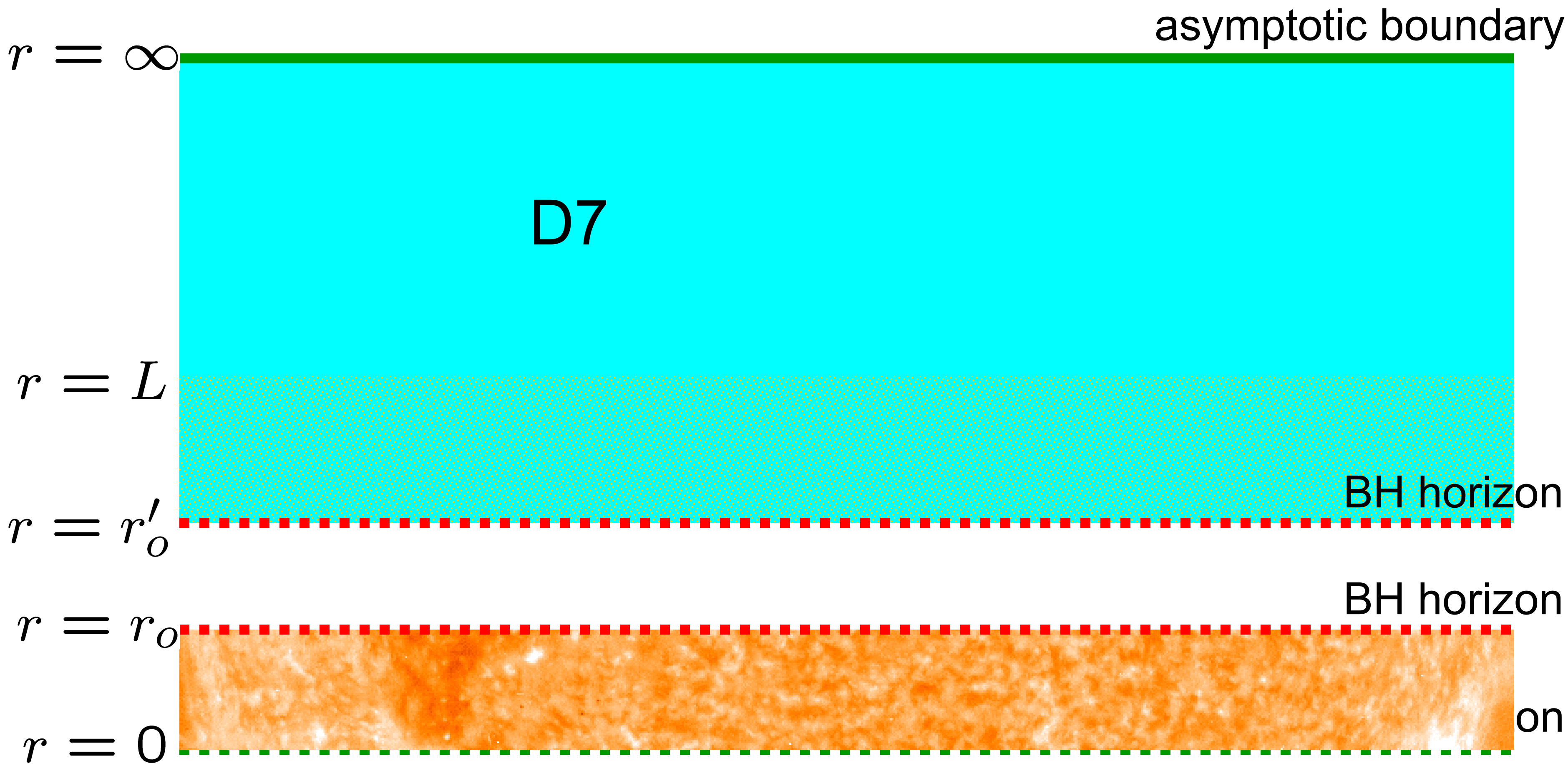
"Mesons", bound states of fundamental fields, dual to open string states supported by D7-brane

<u>Gauge/Gravity thermodynamics with probe branes:</u>

Witten

Gauge theory thermodynamics = Black hole thermodynamics

put D7-probe in throat geometry of black D3-brane



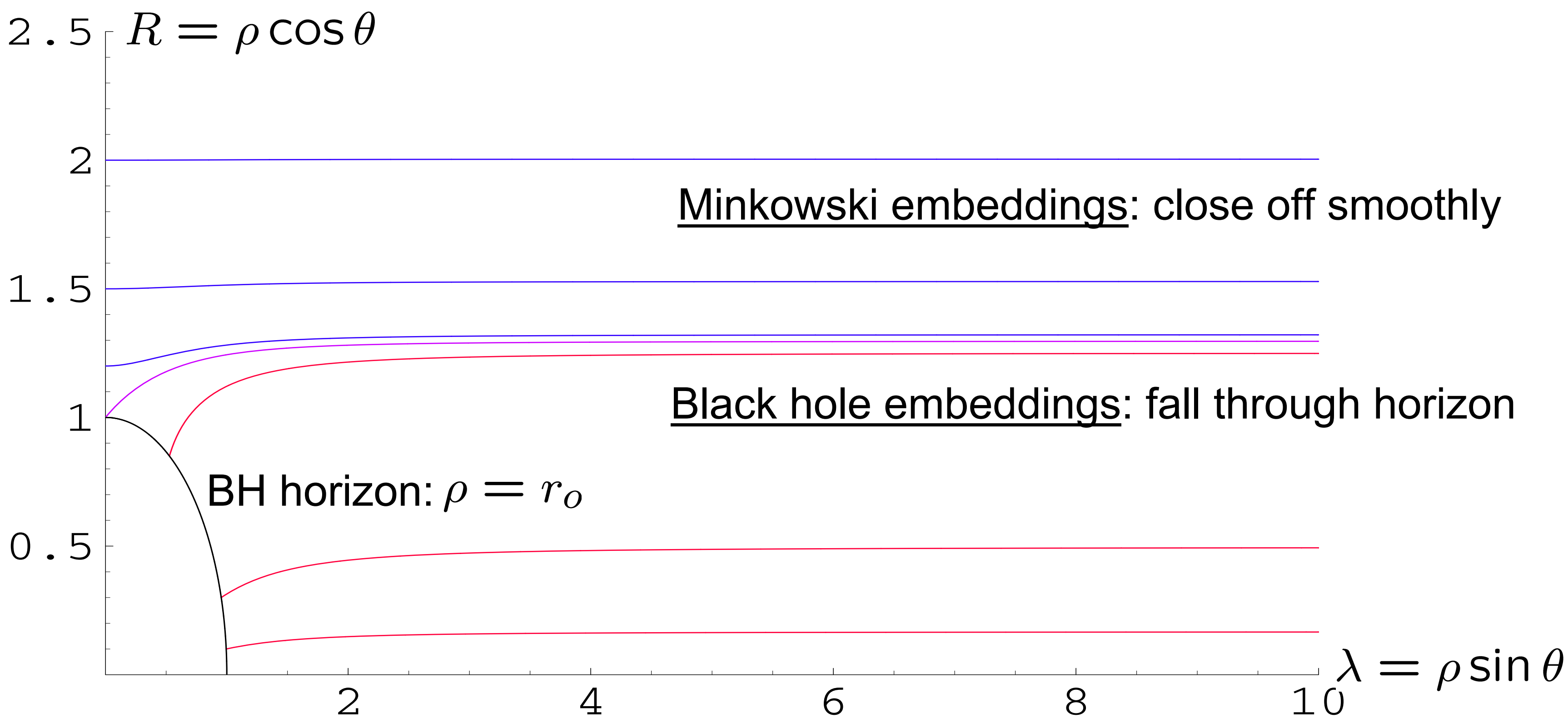
for L ≤ r_o, ... for L sufficiently ... cost at finite r

Expect to see a phase transition!

Babington, Erdmenger, Evans, Guralnik and Kirsch (hep-th/0306018)
Kirsch PhD thesis (hep-th/0406274)

D7-brane embedding in black D3-background:

Numerical solutions:



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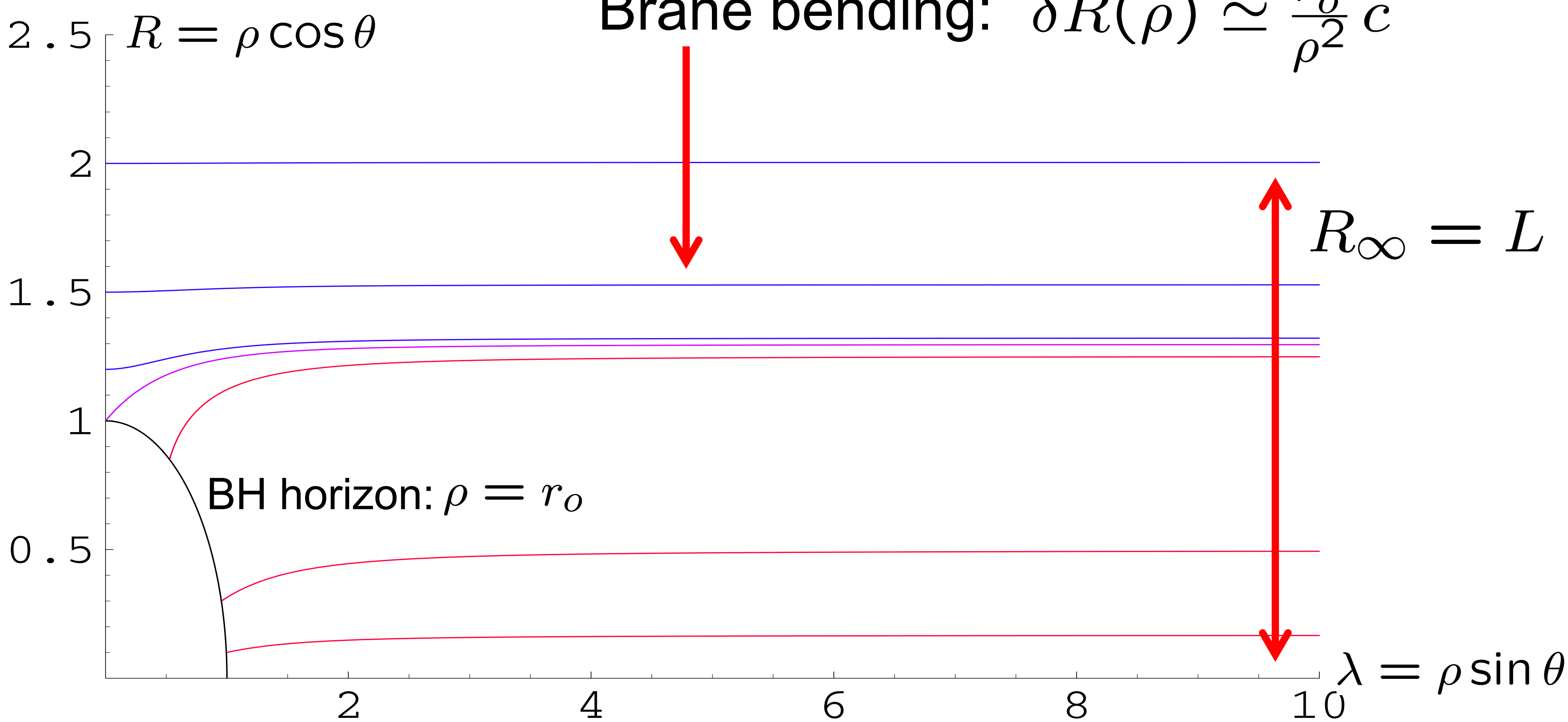
D7-brane embedding in black D3-background:

$$m_q = \frac{L}{2\pi\ell_s^2}\ ; \qquad \langle\bar{\psi}\,\psi\rangle = -\frac{1}{2\sqrt{2}\pi}\sqrt{\lambda}N_c T^3\,\tilde{c}$$

Numerical solutions:

Brane bending: $\delta R(\rho) \simeq \frac{r_o^3}{\rho^2}\,\tilde{c}$



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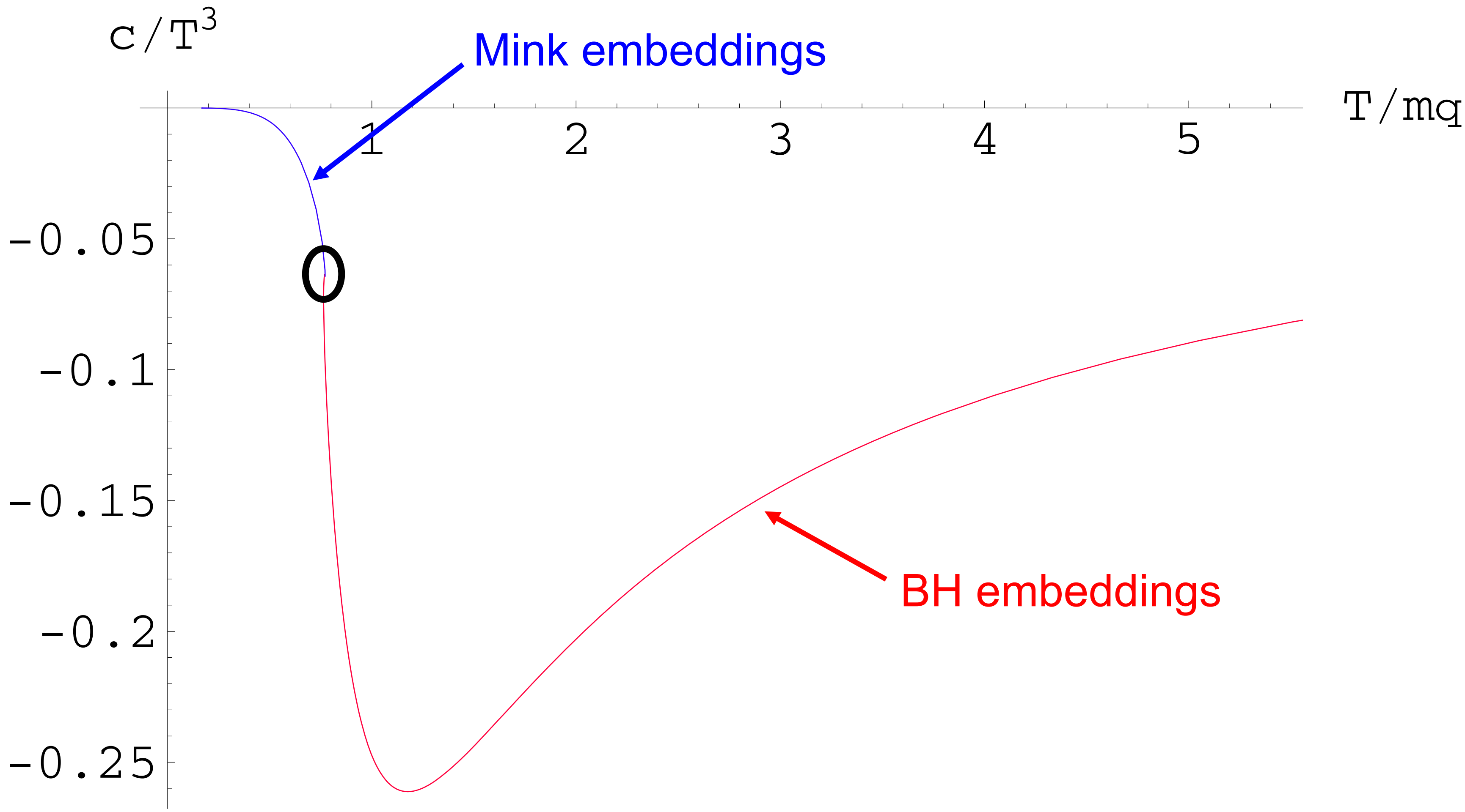
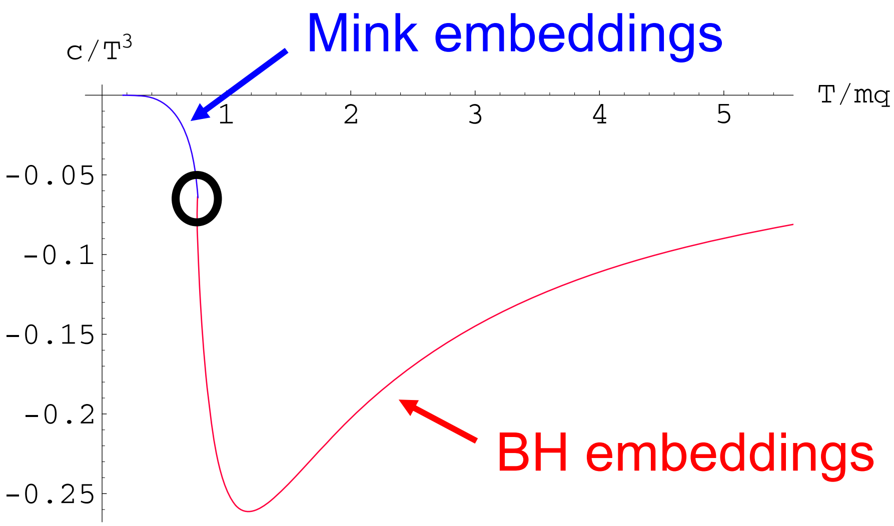
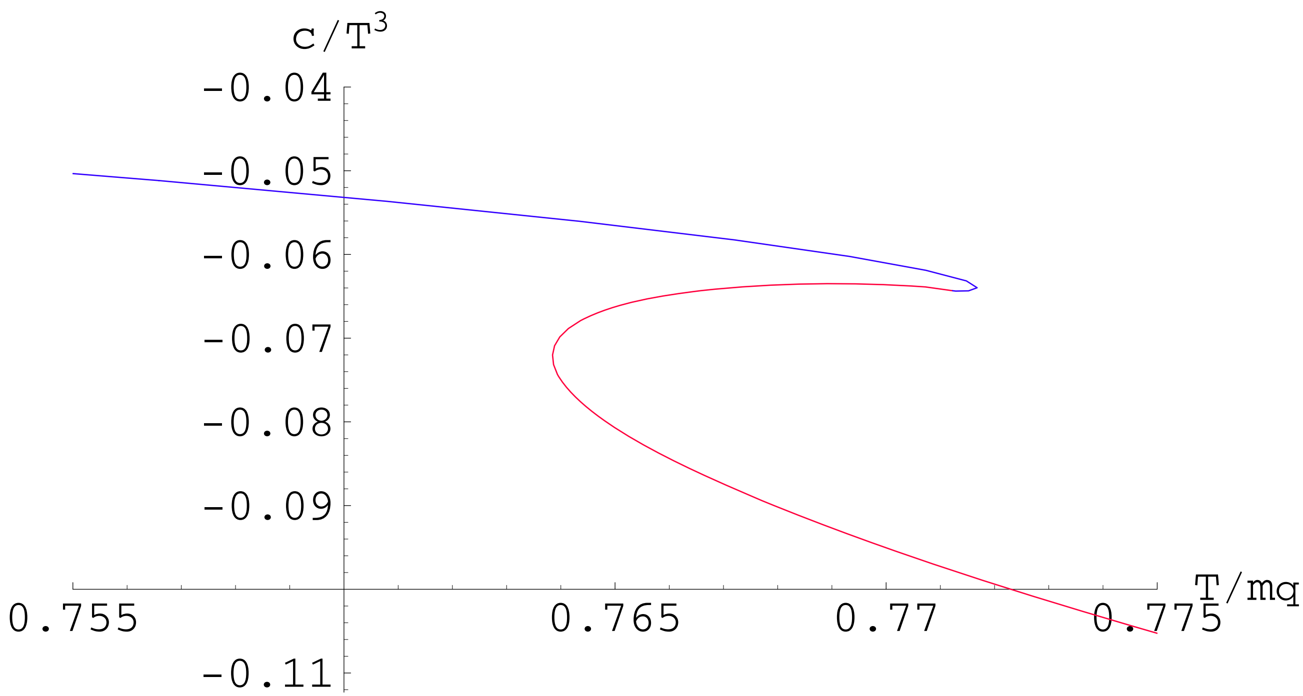


(Phases do not join "smoothly" rather spiral in on critical solution)

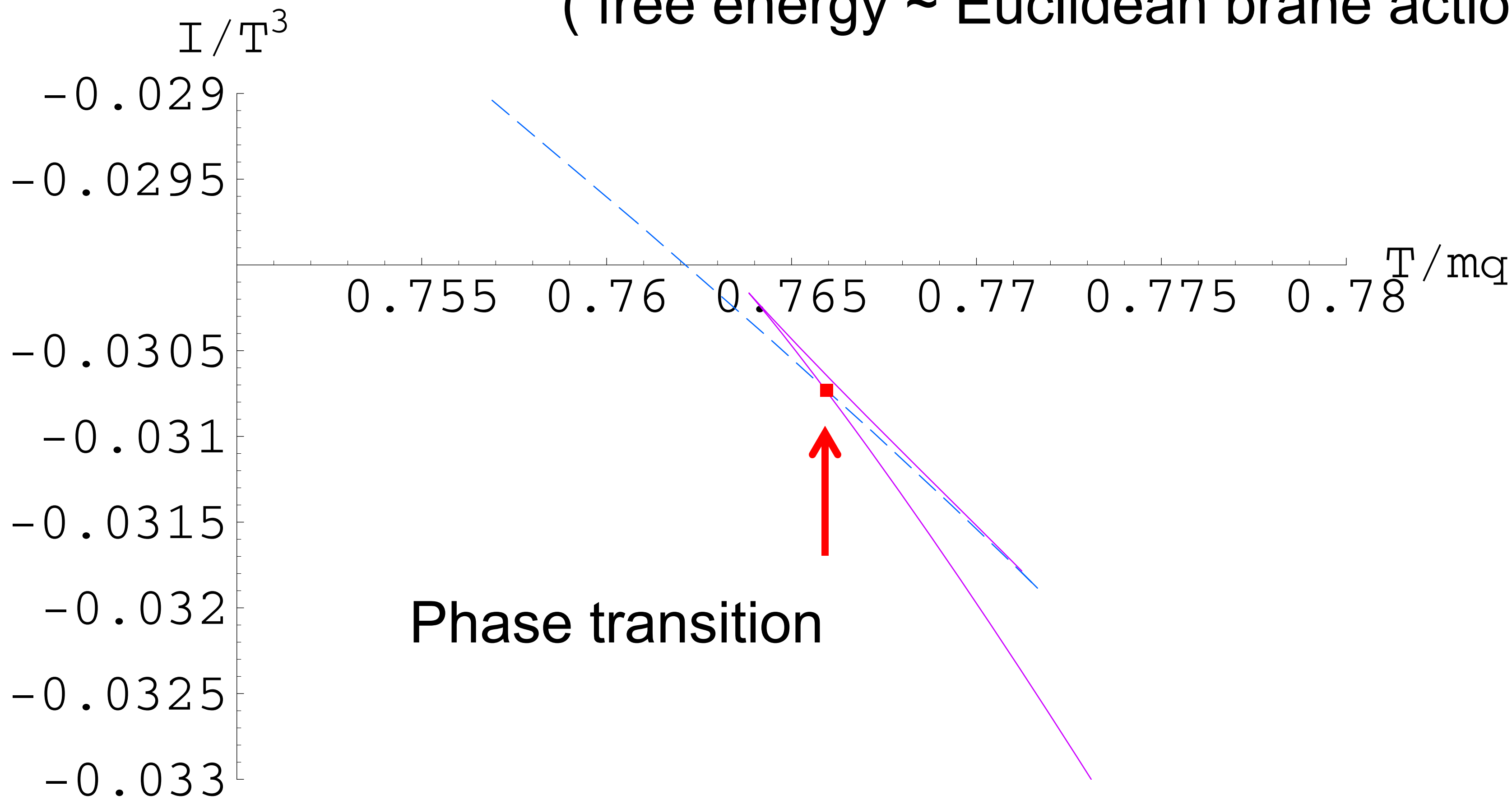
Numerical solutions:





physical properties of thermal system are multi-valued → free energy determines physical configuration

(free energy ~ Euclidean brane action)



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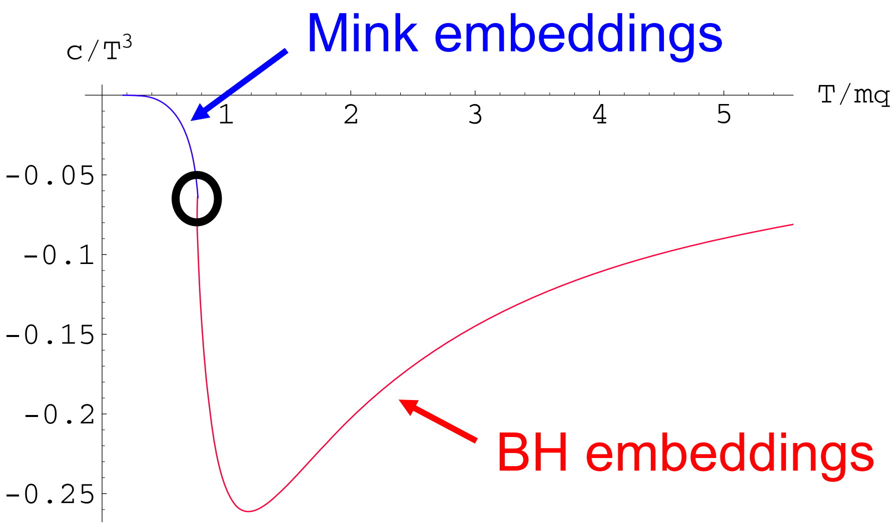
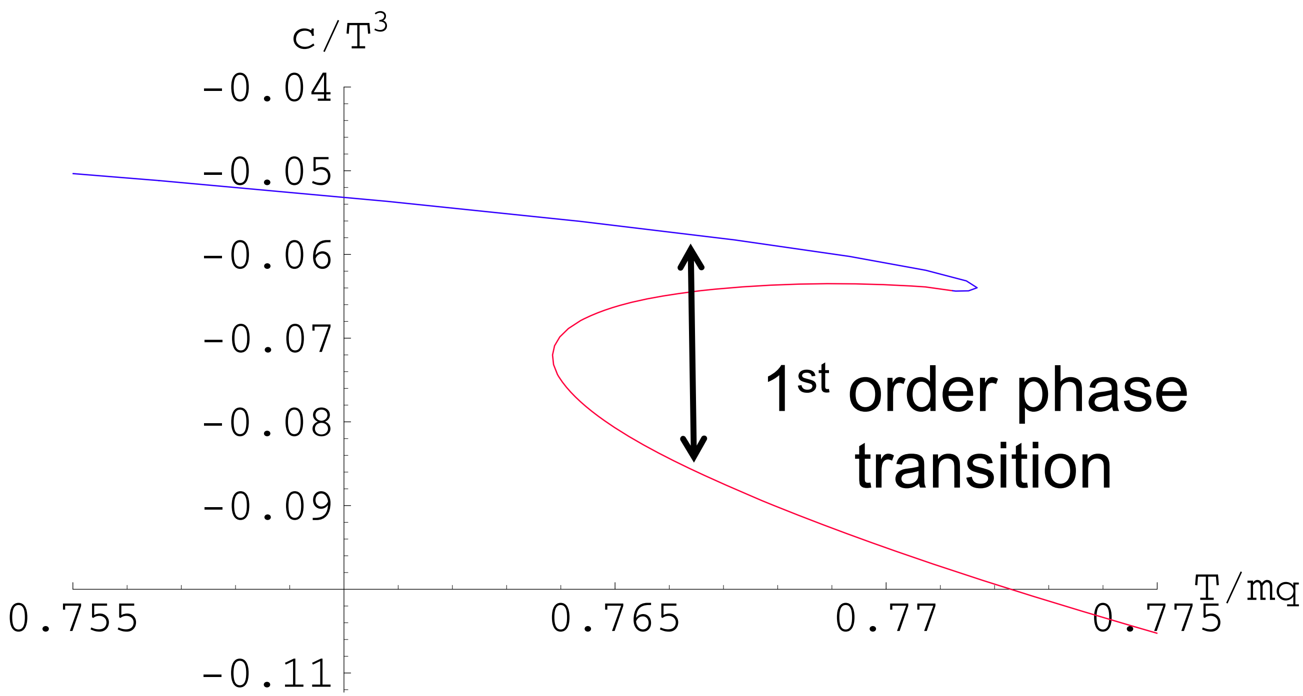
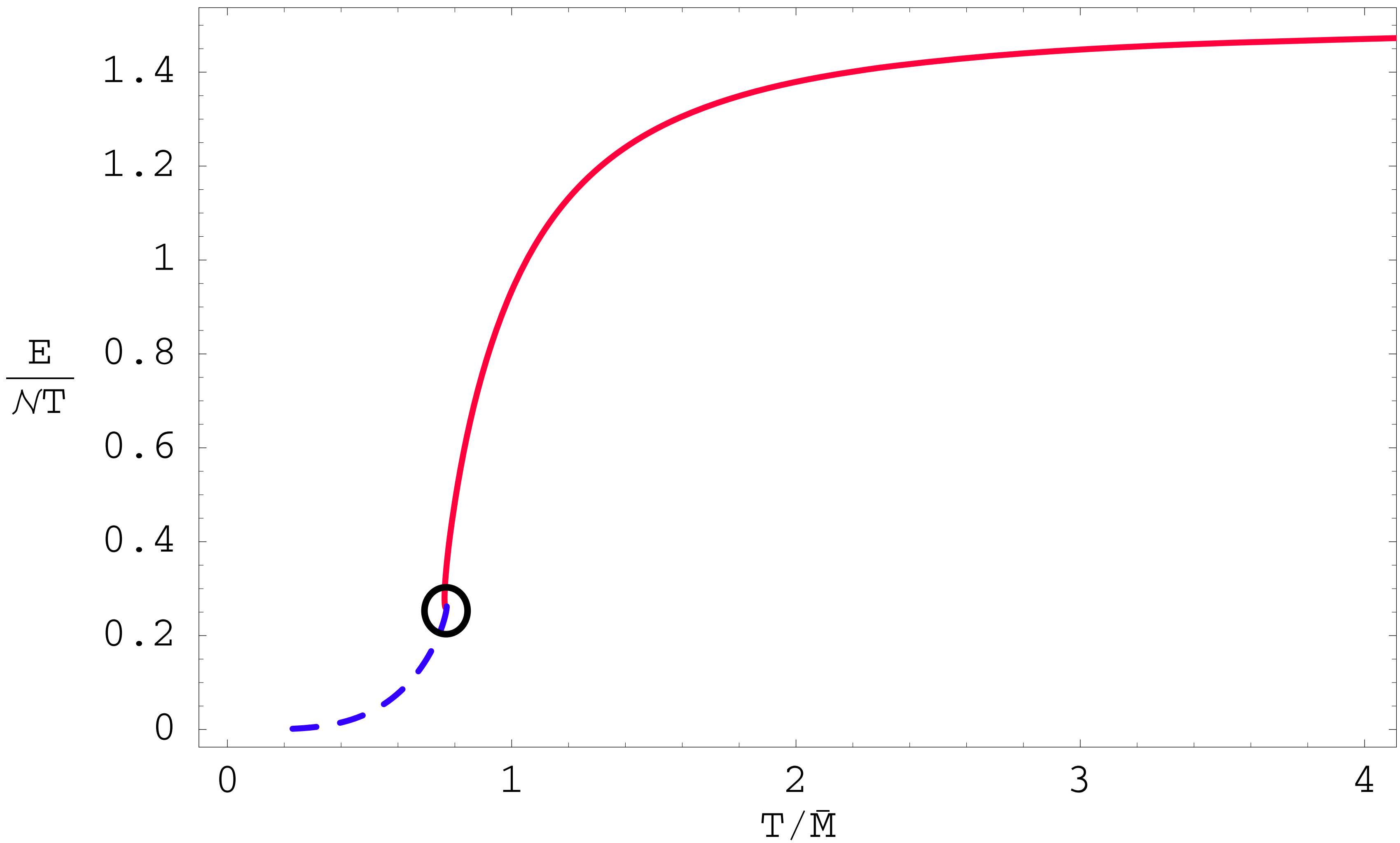




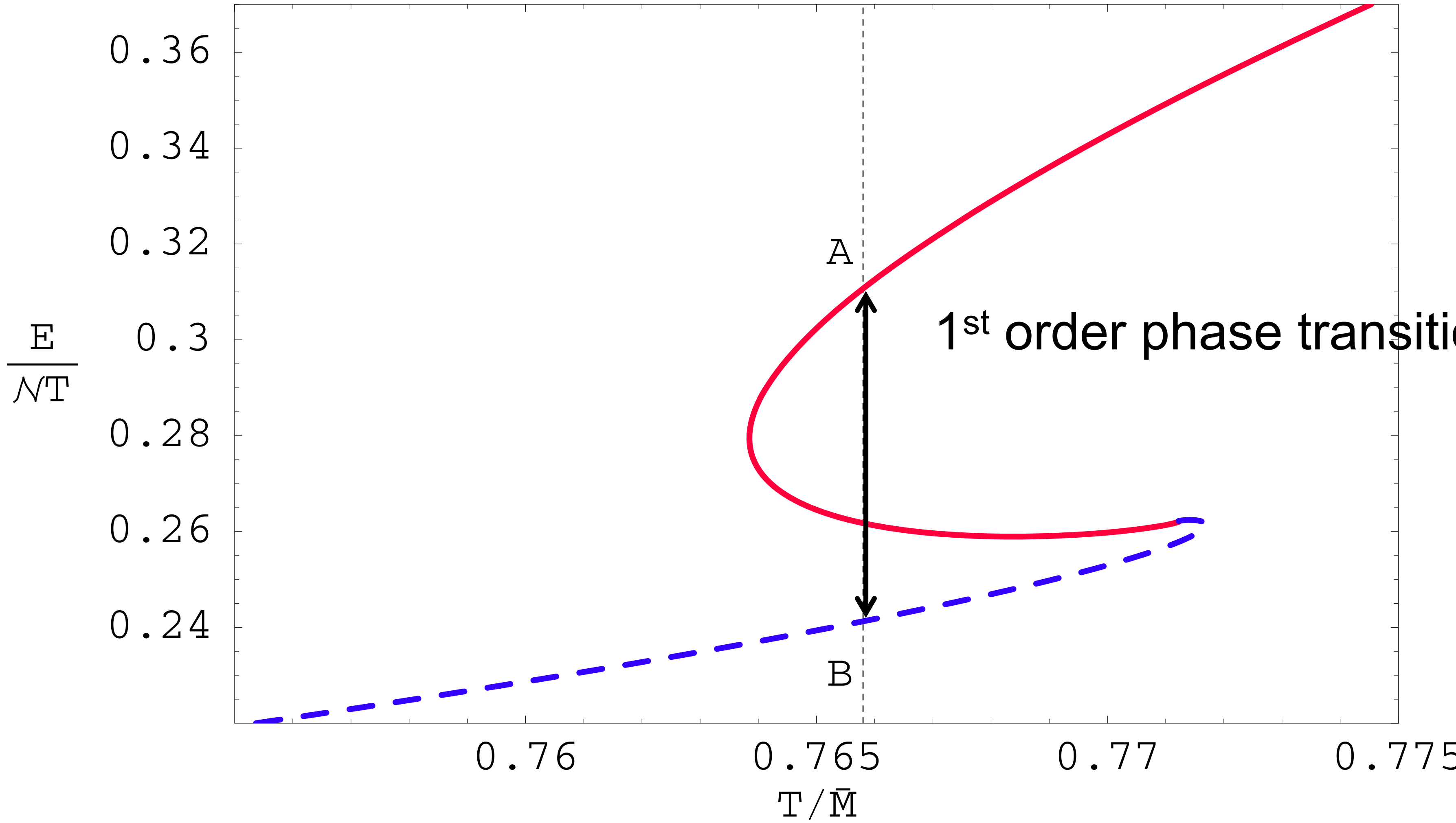
Brane energy:



Brane energy:

Transition temperature:

$T_{fun} \sim m_q/\lambda \sim m_{gap}$



Comments:

• most striking feature is meson spectrum:

Minkowski: discrete stable states	→	black hole: continuous gapless excitations

• 1^{st} order transition → robust

→ persist with $1/N_c$, $1/\lambda$, N_f/N_c corrections

• feature of QCD ??

Consider strange quarks: heavy but strongly coupled

$M(\Phi) = 1020$ MeV → $T_{fun} \sim \frac{.7655}{2\pi} M(\Phi) = 125$ MeV

Compare: $T_c \sim 175$ MeV

study robustness with lattice simulations ??

Transport properties:

- Gauge/gravity duality relates hydrodynamic properties of strongly-coupled plasma to dynamics of AdS black hole

deviations from equilibrium in plasma ⟷ gravitational probes/fluctuations

- variety of transport coefficients:

  ⟶ shear viscosity, bulk viscosity, charge diffusion, ...

Shear viscosity:

[Policastro, Son & Starinets]

$$\eta \;=\; \lim_{\omega\to 0} \frac{1}{2\omega} \int d^4x\, e^{i\omega t}\, \langle [T_{xy}(x), T_{xy}(0)] \rangle$$

- evaluated as particular gravity correlator: $\langle h_{xy}(x) h_{xy}(0) \rangle$

[Son & Starinets; Herzog & Son]

following: Kovtun, Son & Starinets (hep-th/0309213)

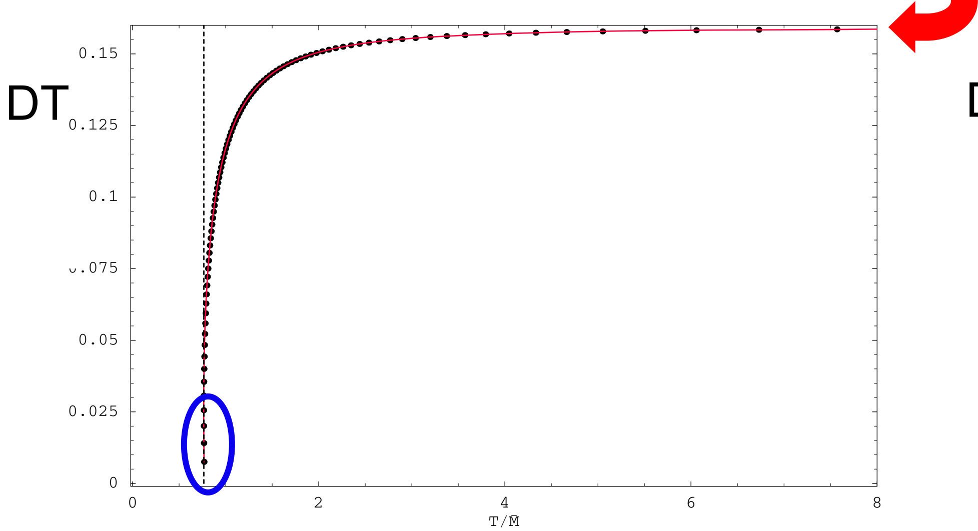
Diffusion of flavor charge (in BH phase)

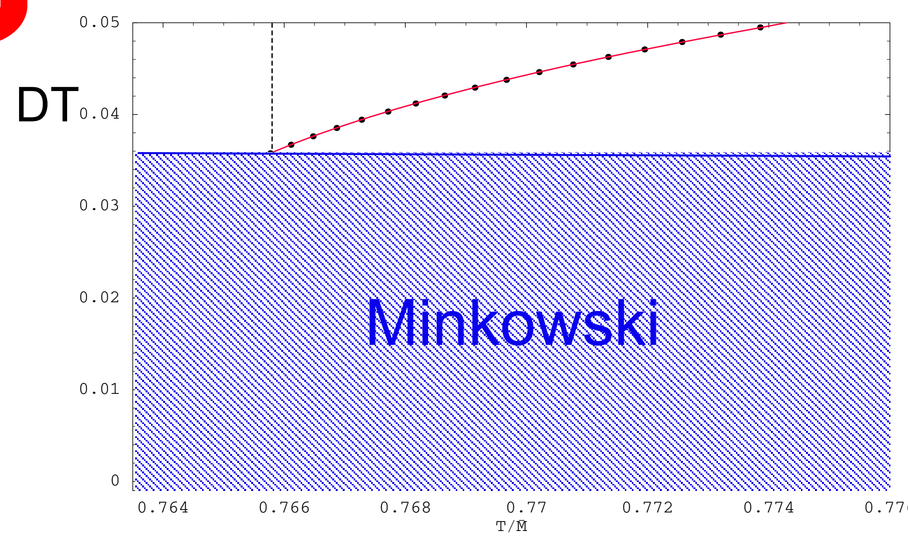
- conserved current: $\partial_\mu J^\mu = 0$

$$J^{ij}_\mu \simeq \mathrm{Tr}\left[\bar{\psi}^i \gamma_\mu \psi^j + \Phi^i D_\mu \Phi^j\right] \;\leftrightarrow\; A^{ij}_\mu$$

- with appropriate bc, Fick's law: $J^x = -\,\mathbf{D}\,\partial_x J^0$
- hydrodynamic mode: $\partial_0 J^0 = -iD\,\partial_x^2 J^0 \longrightarrow \omega = -iD\,q^2$

matches KSS result for R-charge: $D = \dfrac{1}{2\pi T}$





Shear viscosity:

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- evaluated as particular gravity correlator: $\langle h_{xy}(x) h_{xy}(0) \rangle$

[Son & Starinets; Herzog & Son]

- "diffusion constant" for conserved stress-energy

[Policastro, Son & Starinets]

- gravity result: $\eta = \frac{\pi}{8} N_c^2 T^3$

- "small" – compare perturbative results: $\eta \sim \frac{N_c^2 T^3}{\lambda^2 \log(1/\lambda)}$
  – compare RHIC results

- universal result for all known theories with gravity dual:

$$\boxed{\eta/s = 1/4\pi}$$

[Kotvun, Son & Starinets; Buchel & Liu; Saremi; . . . .]

(correction at $O(\lambda^{-3/2})$ increases ratio [Buchel, Liu & Starinets])

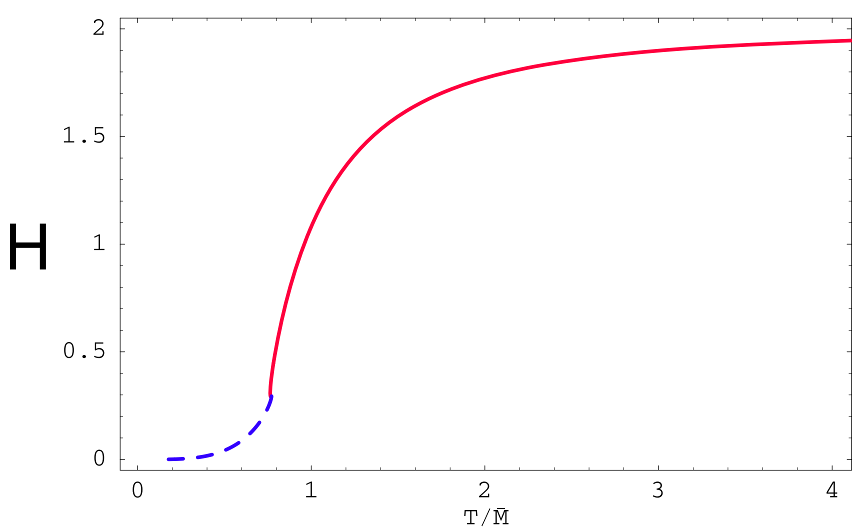
Shear viscosity: extend to calculate contributions of fundamental matter

- probe brane does not disturb universal result: $\eta/s = 1/4\pi$

⟶ calculated for limit M_q=0 and general arguments

- leading order contribution:

$$\eta = \frac{\pi}{8} N_c^2 T^3 \left(1 + \boxed{\frac{\lambda}{16\pi^2} \frac{N_f}{N_c} H\left(\frac{T}{M_q/\lambda}\right)} + O\left(\frac{N_f}{N_c}, \frac{1}{\lambda^{3/2}}, \frac{1}{N_c^2}, \lambda \frac{N_f^2}{N_c^2}\right) \right)$$



Conclusions/Outlook:

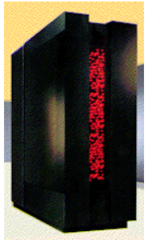
- D3/D7 system: interesting framework to study quark/meson contributions to strongly-coupled nonAbelian plasma

- first order phase transition appears as universal feature of holographic theories with fundamental matter ($T_f > T_c$)

- how robust is this transition?

  ⟶ should survive finite $1/N_c$, $1/\lambda$, N_f/N_c corrections

  ⟶ interesting question for lattice investigations



- hydrodynamic transport properties: (in progress)

⟶ shear viscosity still universal: $\eta/s = 1/4\pi$

⟶ thermal spectral functions

- adding chemical potential/finite baryon density