Title: Holographic Theories with Fundamental Matter

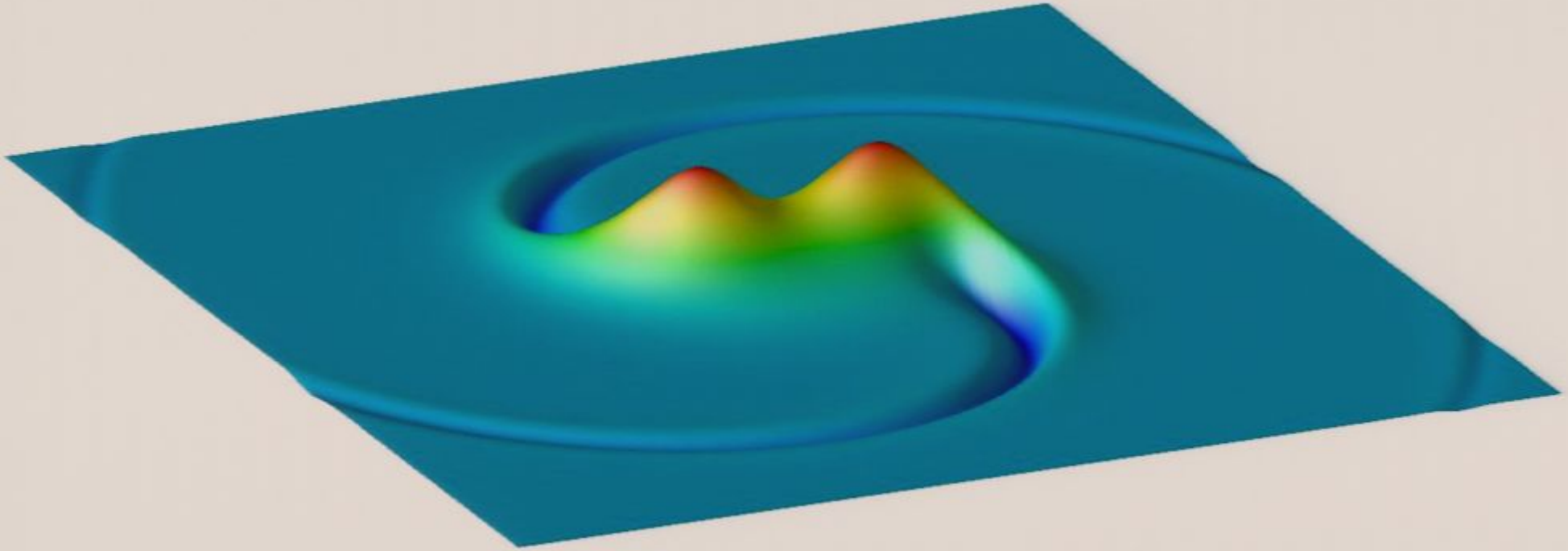
Date: May 24, 2007 02:00 PM

URL: http://pirsa.org/07050068

Abstract:

Exotic States of Hot and Dense Matter and their Dual Description
May 22 – 25, 2007

Holographic Theories with Fundamental Matter



with David Mateos, Rowan Thomson, Andrei Starinets, Shunji Matsuura, Shimpei Kobayashi, Jordan Hovdebo, Sean Gryb, Martin Kruczenski & David Winters

Outline:

1. Gauge/Gravity duality with fundamental fields
   $\longrightarrow$ add probe branes

2. Probe branes in thermal backgrounds
   $\longrightarrow$ first-order phase transition;
   "mesons melting"

3. Transport properties of plasma
   $\longrightarrow$ diffusivity, viscosity, spectral functions, ...

4. Conclusions/Outlook

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Maldacena; Witten; Gubser, Klebanov & Polyakov; .....

AdS/CFT from D3-branes:

d=10 Type IIb superstrings in $AdS_5 \times S^5$
with N_c units of RR flux

equivalent to

d=4 $\mathcal{N}$ =4 $U(N_c)$ super-Yang-Mills

$$g_{YM}^2 = 2\pi g_s \ll 1$$
$$\lambda \equiv g_{YM}^2 N_c = \tfrac{1}{2}\left(R^2/\alpha'\right)^2 \gg 1$$

supergravity limit ~ large-N with strong `t Hooft coupling

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all adjoint fields!

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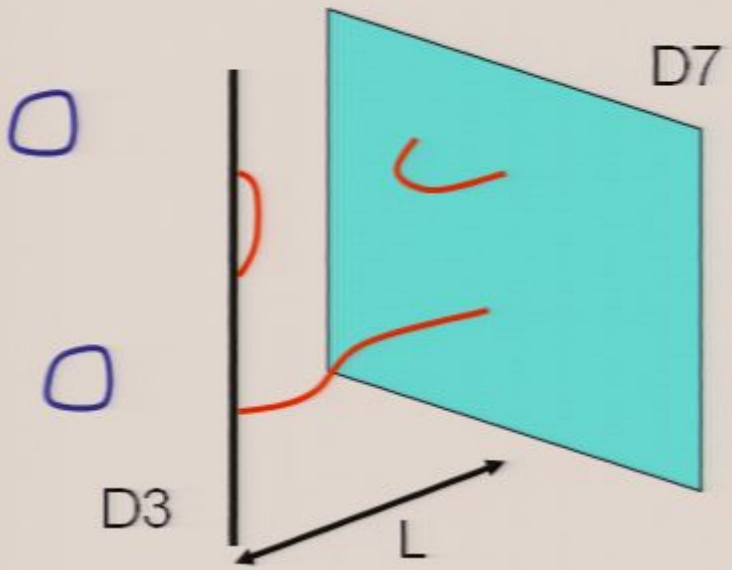
Adding flavor to AdS/CFT:

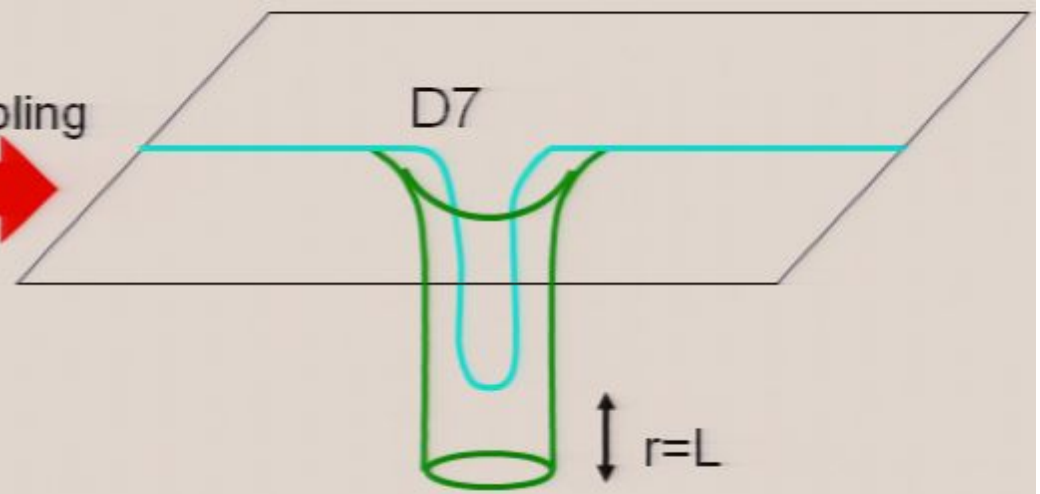
Karch and Katz (**hep-th/0205236**)

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

N coincident D3-branes:



Strong coupling



black brane with $R^4 \sim g_s N_c \alpha'^2$

d=4 $U(N_c)$ o.s., d=8 $U(N_f)$ o.s.
& bifundamental 3-7 o.s.

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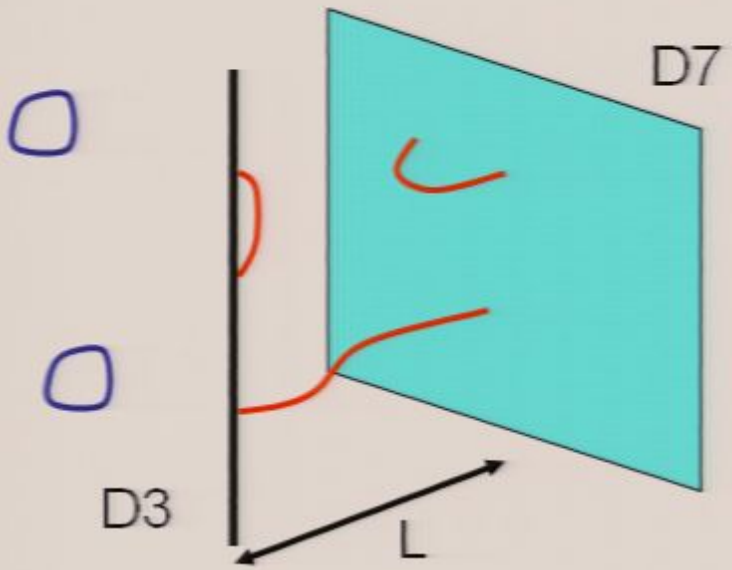

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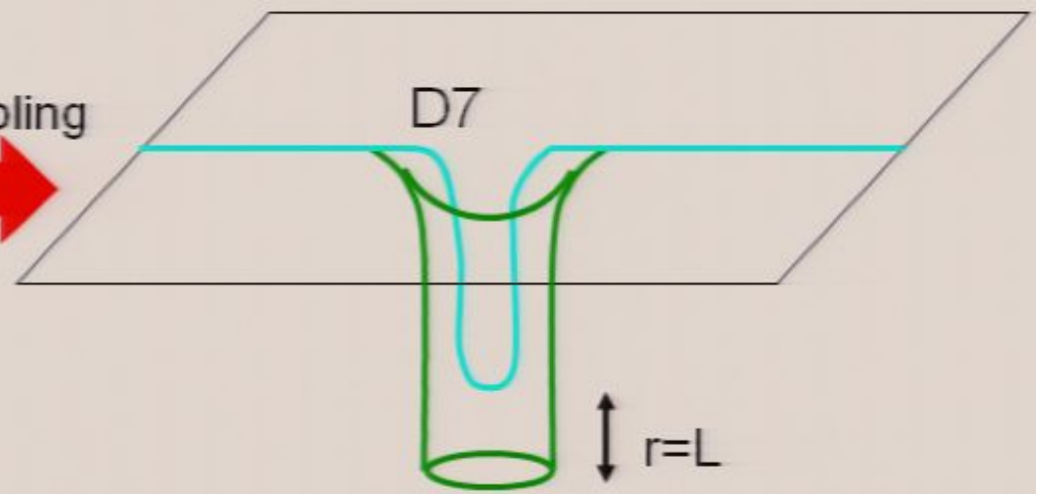

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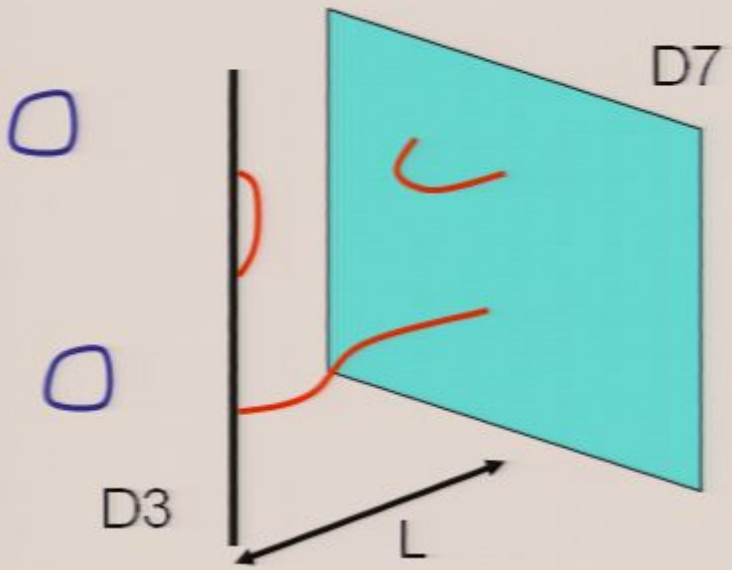

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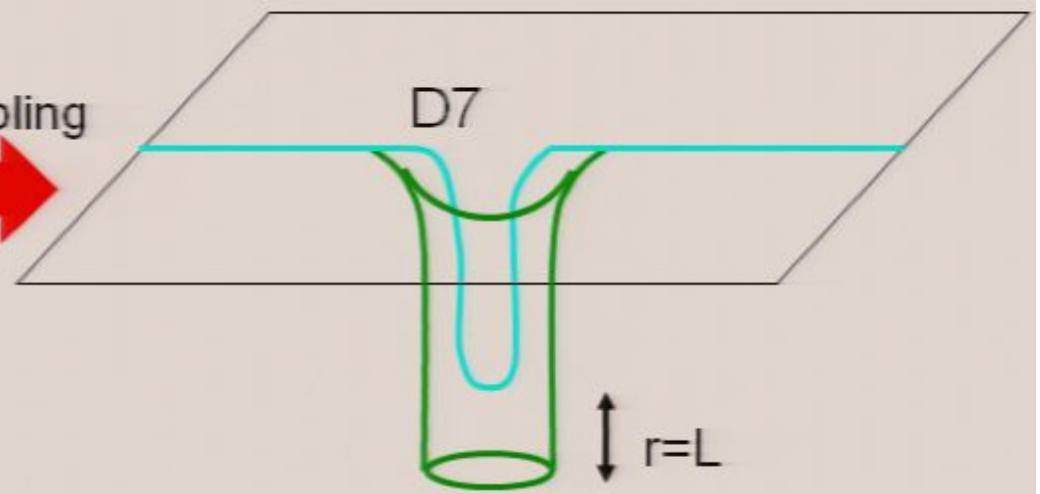

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Decouples asymptotic (closed) strings

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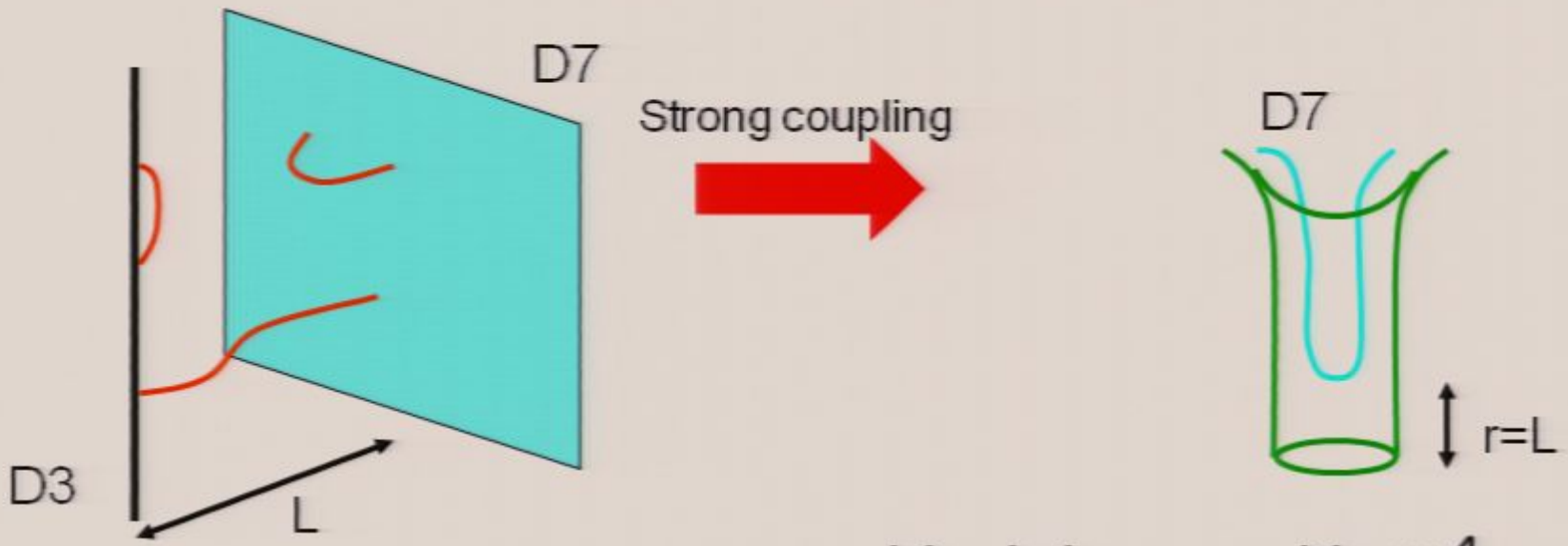

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Reduces brane theory to field theory

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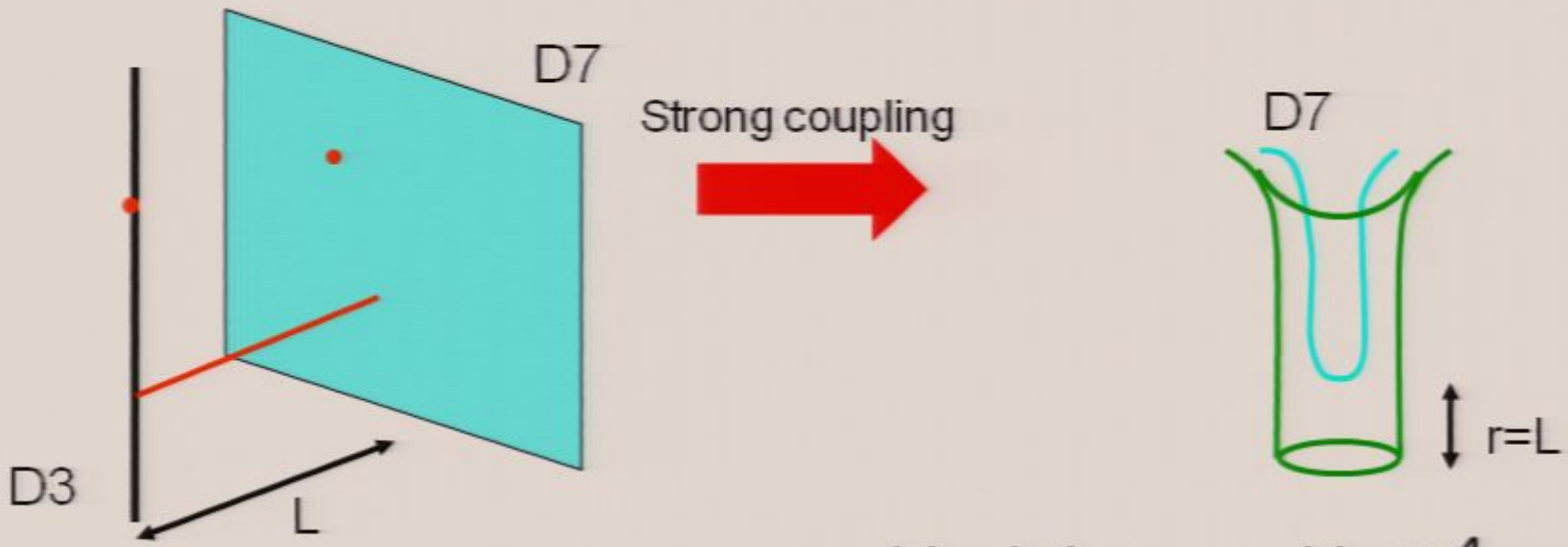

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Minimum mass for 3-7 strings: $m_q = \frac{L}{2\pi\alpha'}$

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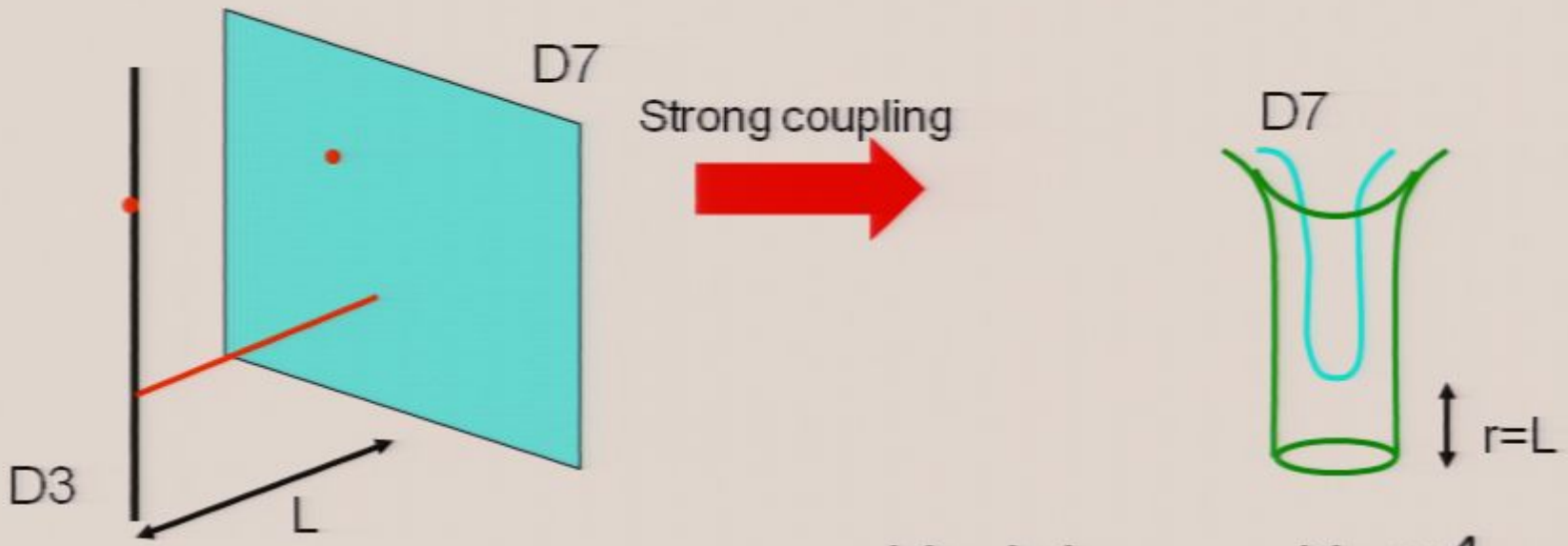

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Gauge coupling on D7's: $g_{YM}^2 \sim g_s \alpha'^2 \to 0$

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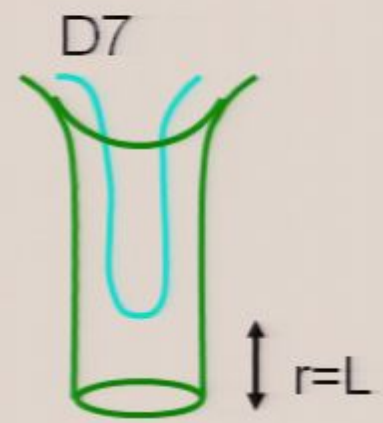

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Low-energy limit with $\alpha' E^2, L^2/\alpha' \to 0$

- throat geometry: $AdS_5 \times S^5$ with N_f D7's
- brane theory $\to$ $\mathcal{N}$=4 $U(N_c)$ SYM with fundamental matter

Field theory:

$\mathcal{N}$=4 U(N_c) super-Yang-Mills

vector:	$(A_\mu)^a{}_b$
4 Weyl fermions:	$(\psi_{1,2,3,4})^a{}_b$
3 complex scalars:	$(\phi_{1,2,3})^a{}_b$

} adjoint in U(N_c)

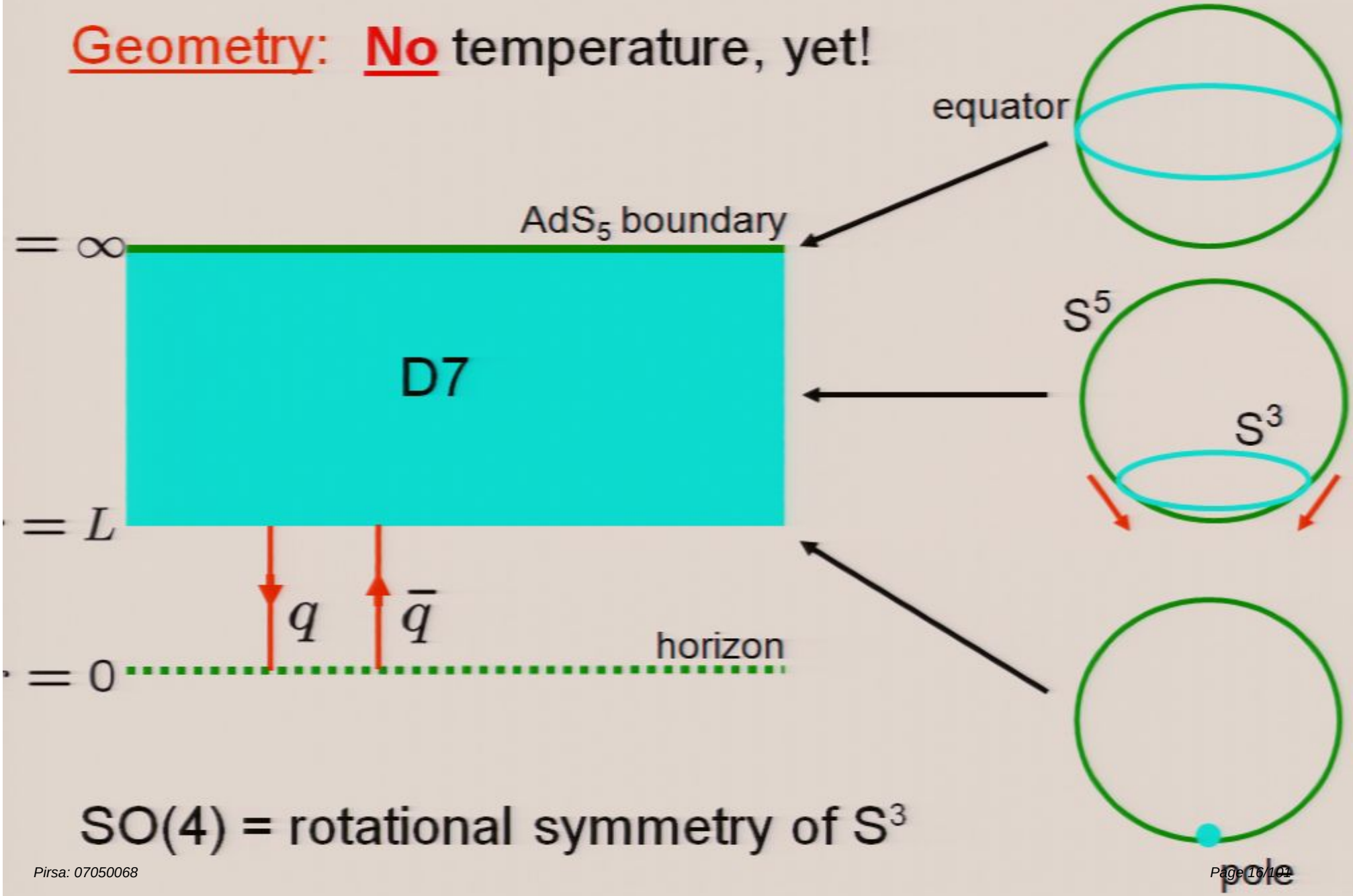
coupled to: N_f **massive** $\mathcal{N}$=2 hypermultiplets

2 complex scalars :	$(q_i)^a$, $(\tilde{q}^i)_a$
2 Weyl fermions:	$(\psi_i)^a$, $(\tilde{\psi}^i)_a$

} fund. in U(N_c) & global U(N_f)

- SUSY: $\mathcal{N}$=4 $\rightarrow$ $\mathcal{N}$=2
- SO(6) $\rightarrow$ SO(4) = $SU(2)_L$ X $SU(2)_R$

Geometry: No temperature, yet!



SO(4) = rotational symmetry of S^3

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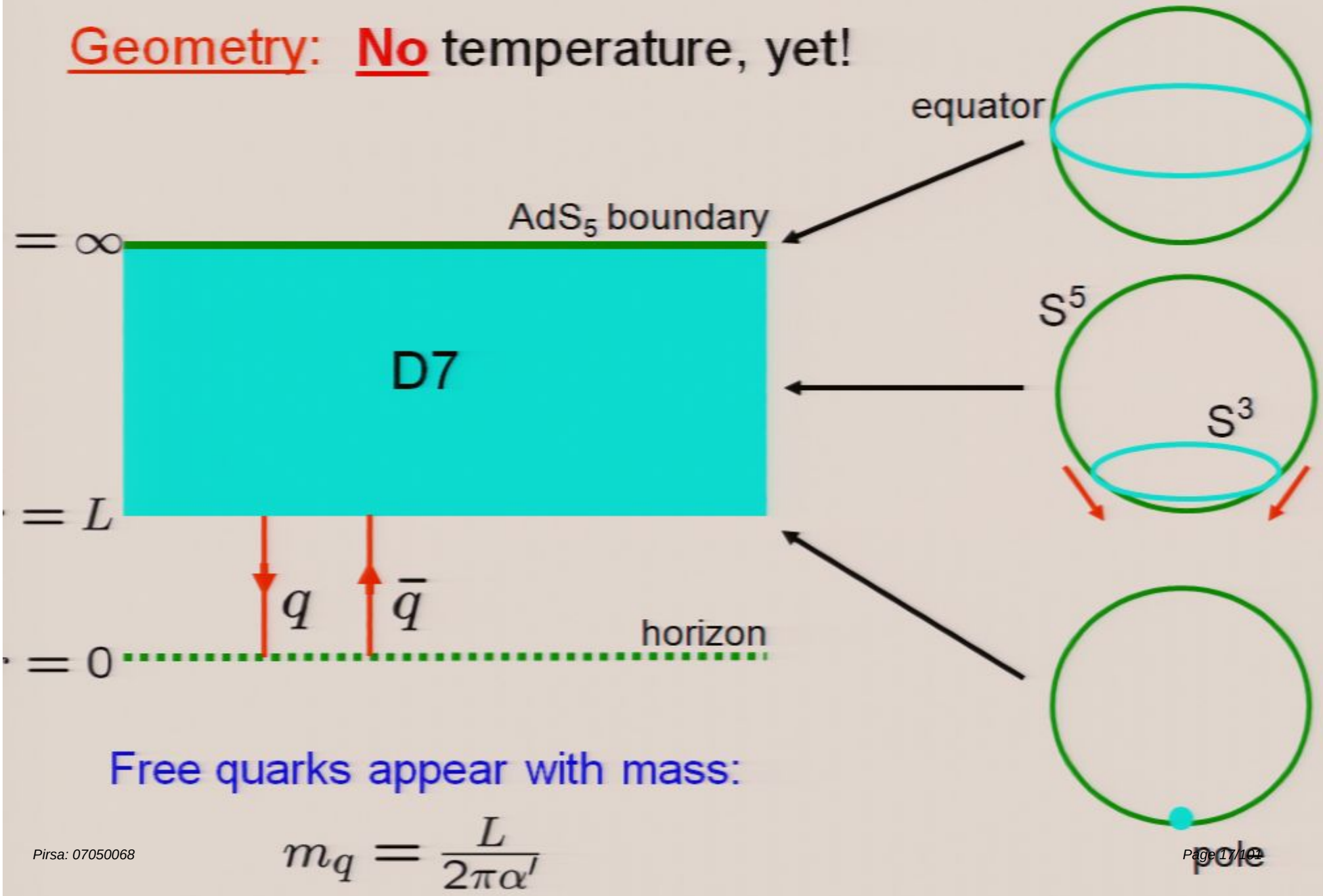
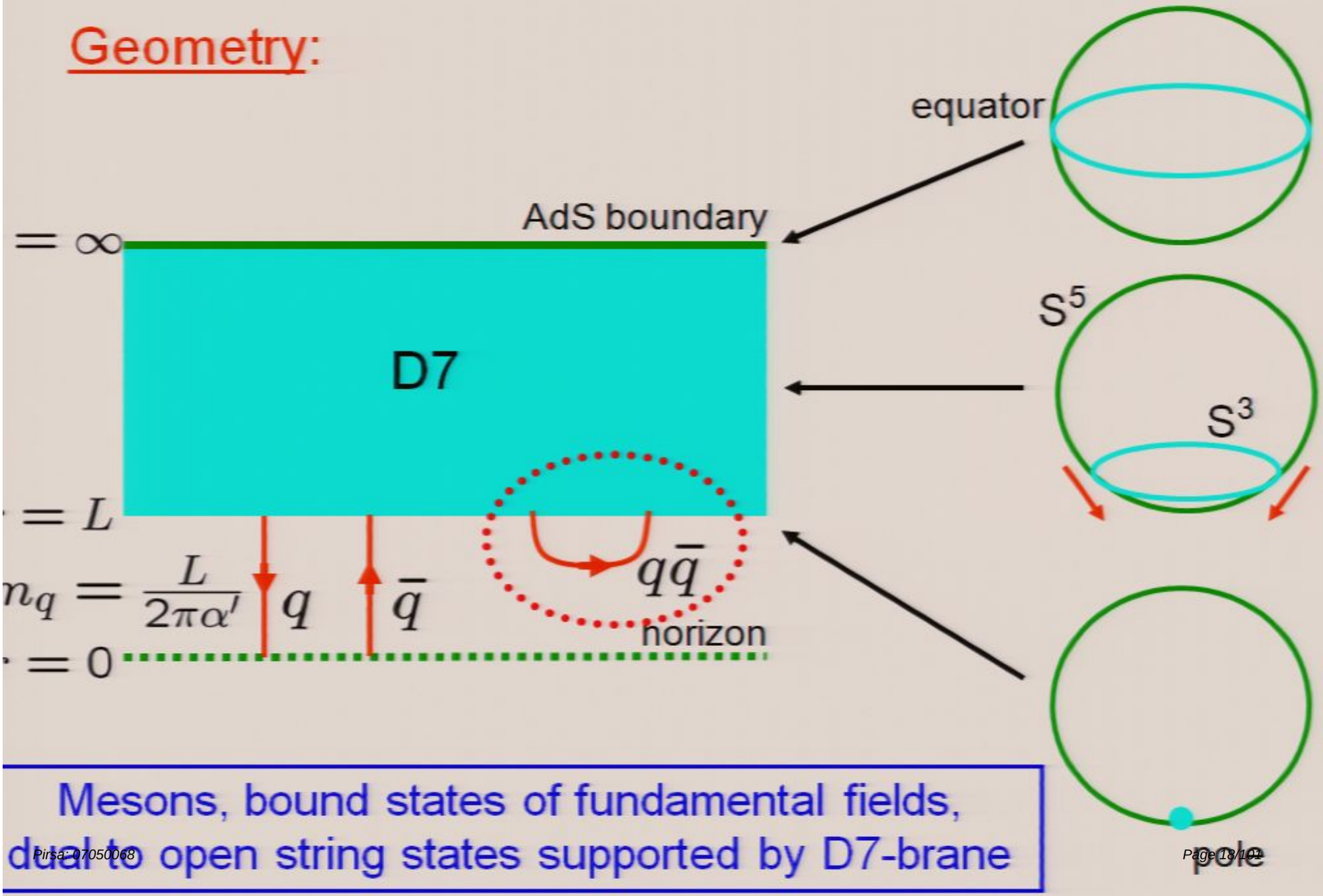


Free quarks appear with mass:

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

Geometry:



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

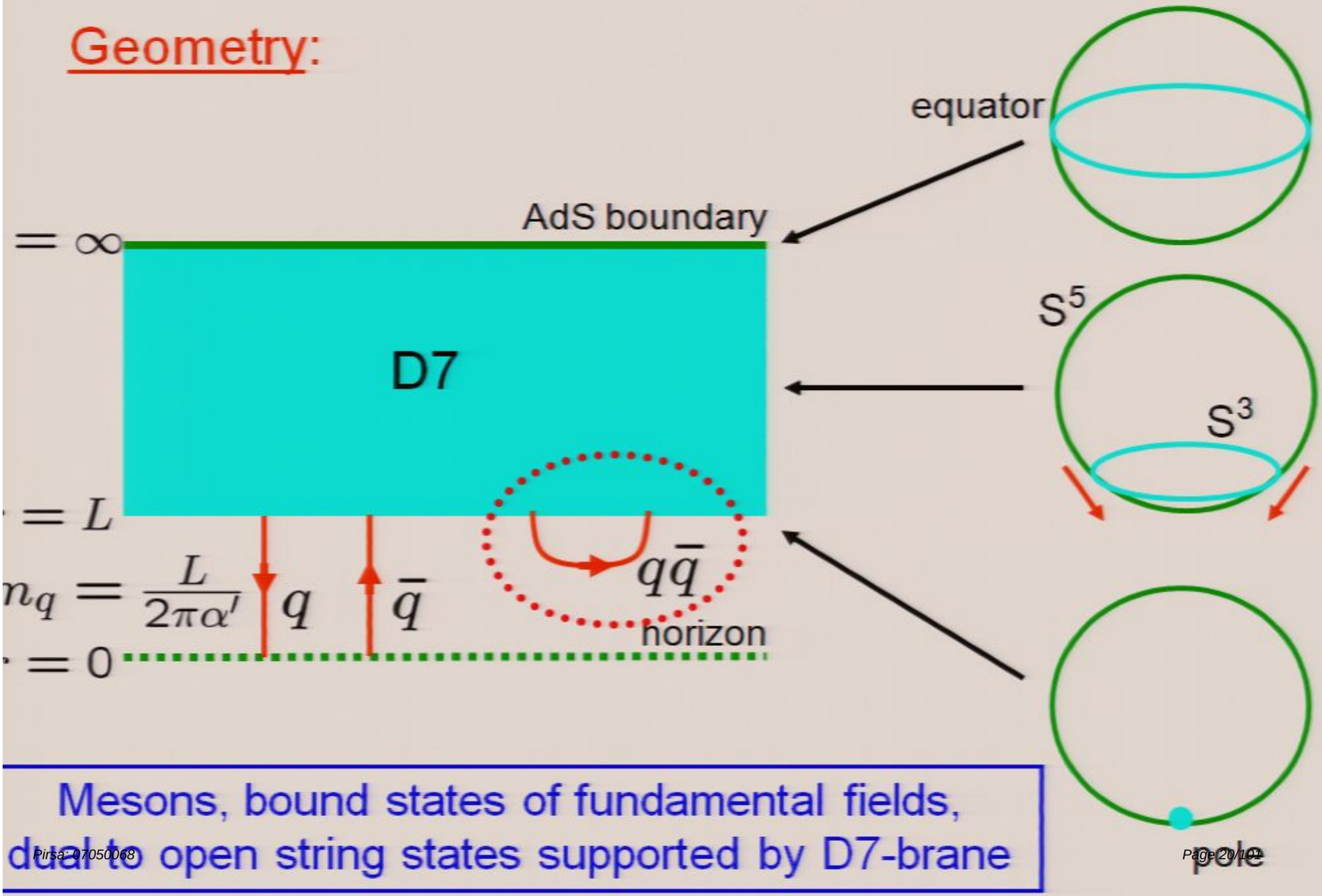
Gauge/gravity dictionary:

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

D7-brane modes:

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

Geometry:



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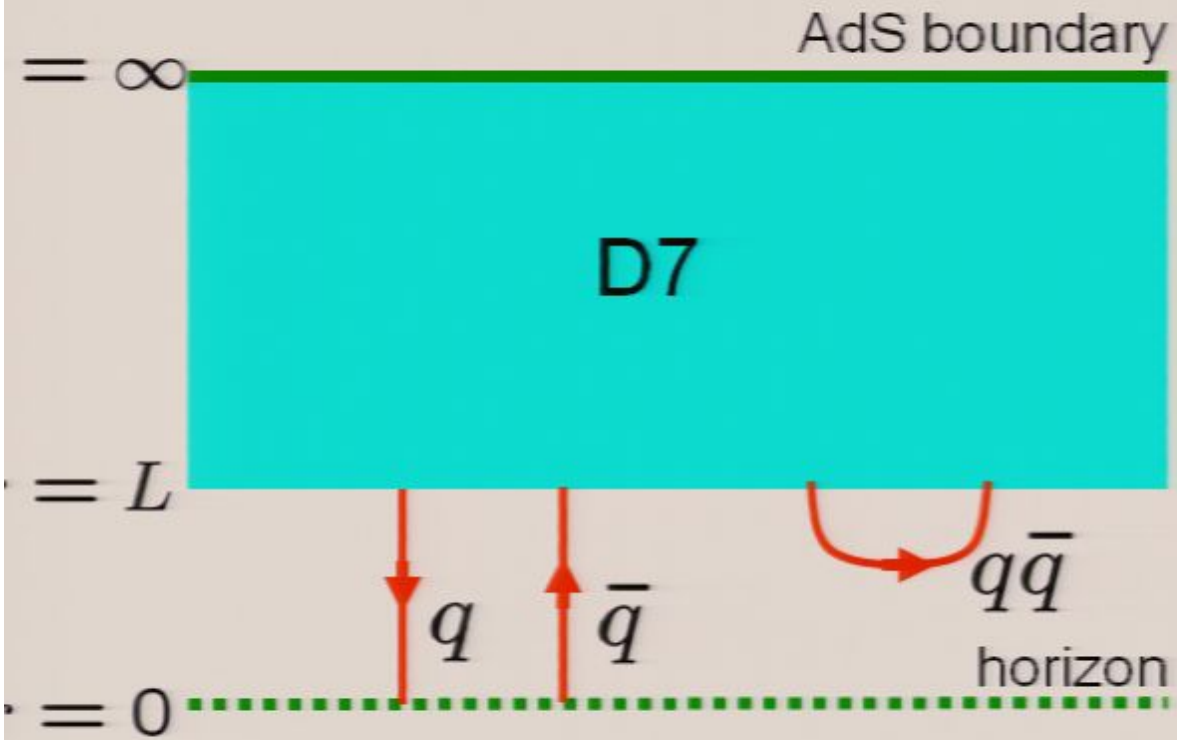

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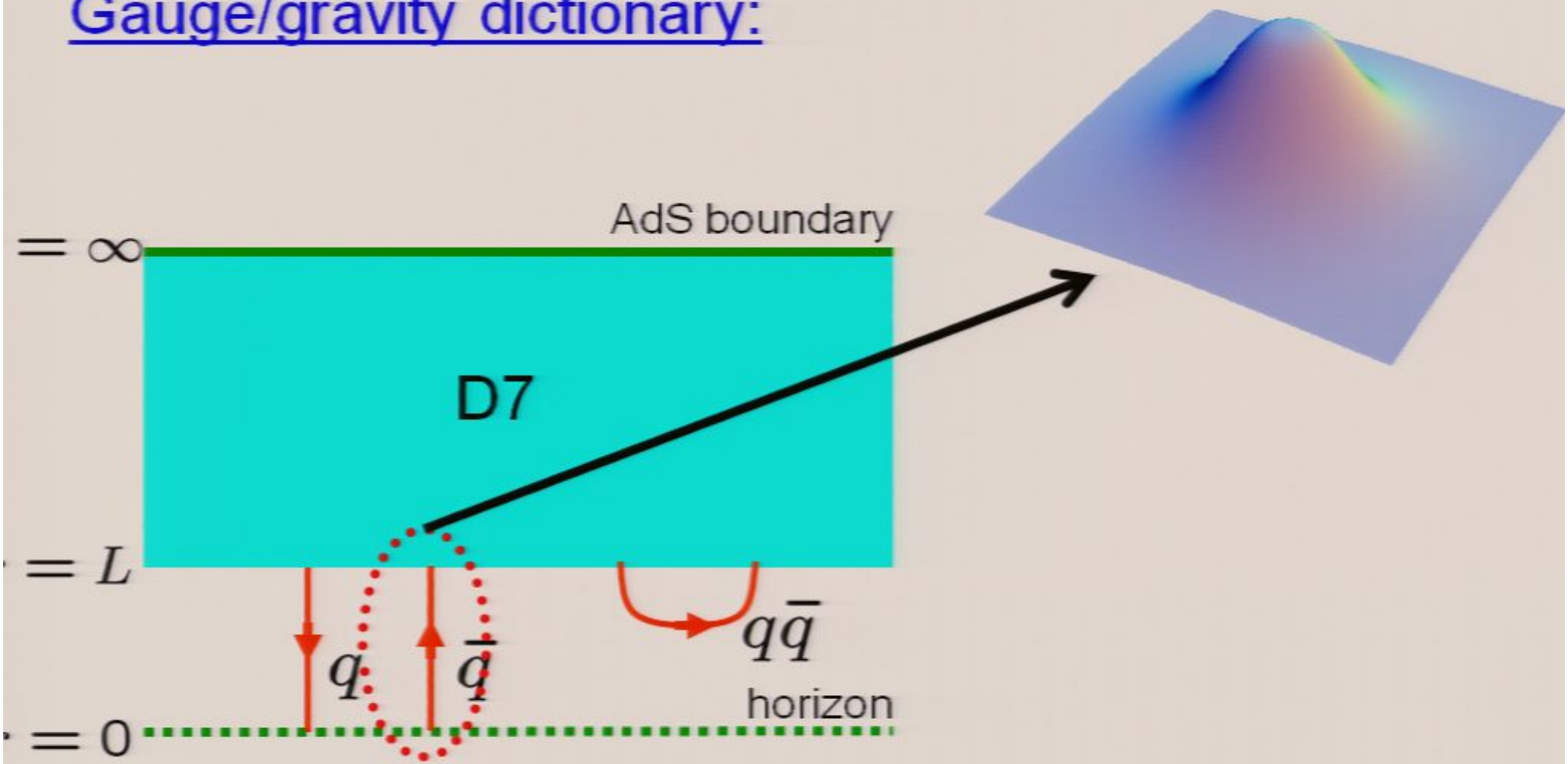

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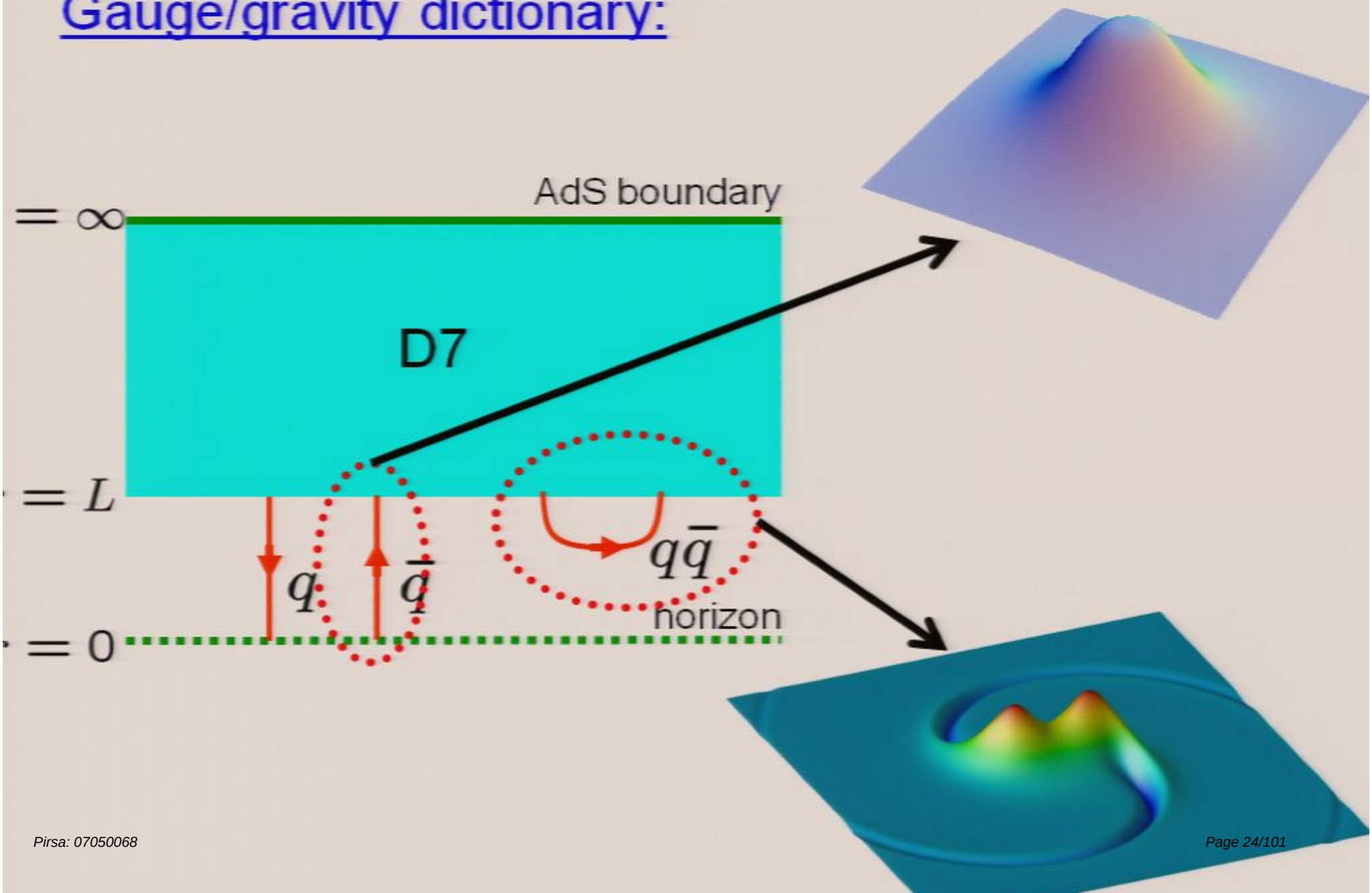

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Probe approximation: $N_f / N_c \to 0$

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)

Kruczenski, Mateos, RCM and Winters
(hep-th/0304032)

Mesons:

lowest lying open string states are excitations of the massless modes on D7-brane: vector, scalars (& spinors)

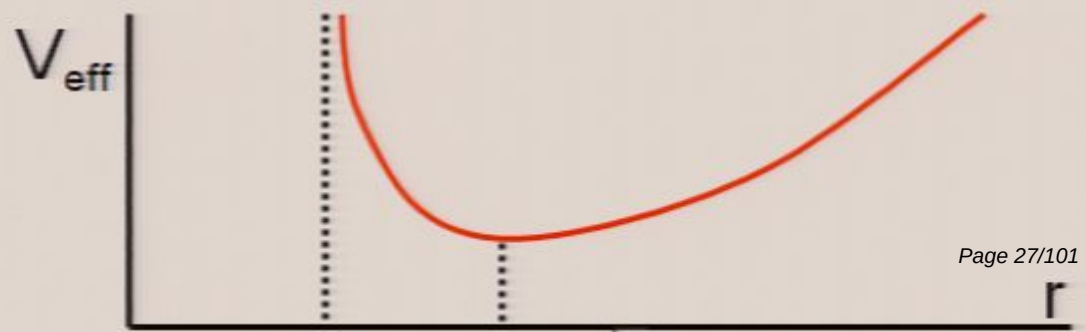
→ their dynamics is governed by usual worldvolume action:

$$S_{D7} = -\frac{1}{(2\pi)^7 g_s \alpha'^4} \int d^8\xi \sqrt{-\det\left(P[G]_{ab} + 2\pi\alpha' F_{ab}\right)} + \frac{1}{2(2\pi)^5 g_s \alpha'^2} \int P[C^{(4)}] \wedge F \wedge F$$

free spectrum:

- expand action to second order in fluctuations
- solve linearized eq's of motion by separation of variables

→ discrete spectrum



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Meson spectrum:

$$M^2(n,\ell) = \frac{4L^2}{R^4}(n+\ell+1)(n+\ell+2)$$

n = radial AdS quantum #

ℓ = angular quantum # on S^3 = R-charge

massive supermultiplets with $8(\ell+1)$ bosons and fermions

$$n=\ell=0 \ : \ m_{\text{gap}} = 2\sqrt{2}\frac{L}{R^2} = 4\pi\frac{m_q}{\sqrt{g_{YM}^2 N_c}} = 4\pi\frac{m_q}{\lambda^{1/2}}$$

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Meson interactions:

Continue expansion of D7-brane action beyond 2nd order

- substitute $\Phi = \phi(x)\psi_{n,\ell}(r)Y_\ell(\Omega)$ and integrate out r and S^3

e.g., $$\mathcal{L}_{eff} \simeq -\frac{1}{2}\left[(\partial\phi)^2 + M^2\phi^2\right] + \underbrace{\frac{2\pi\alpha'}{L}\frac{1}{\sqrt{N}}}\phi(\partial\phi)^2 + \ldots$$

$$g_{\phi(\partial\phi)^2} \simeq \frac{2\pi\alpha'}{L}\frac{1}{\sqrt{N}} = \frac{1}{m}\frac{1}{\sqrt{N}}$$

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Witten; .....

Gauge/Gravity thermodynamics:

Gauge theory thermodynamics = Black hole thermodynamics

- Replace SUSY D3-throat with throat of black D3-brane
- Wick rotate and use euclidean path integral techniqes
- . . . . .

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Here we would like to extend these ideas to include contributions of probe branes/fundamental matter

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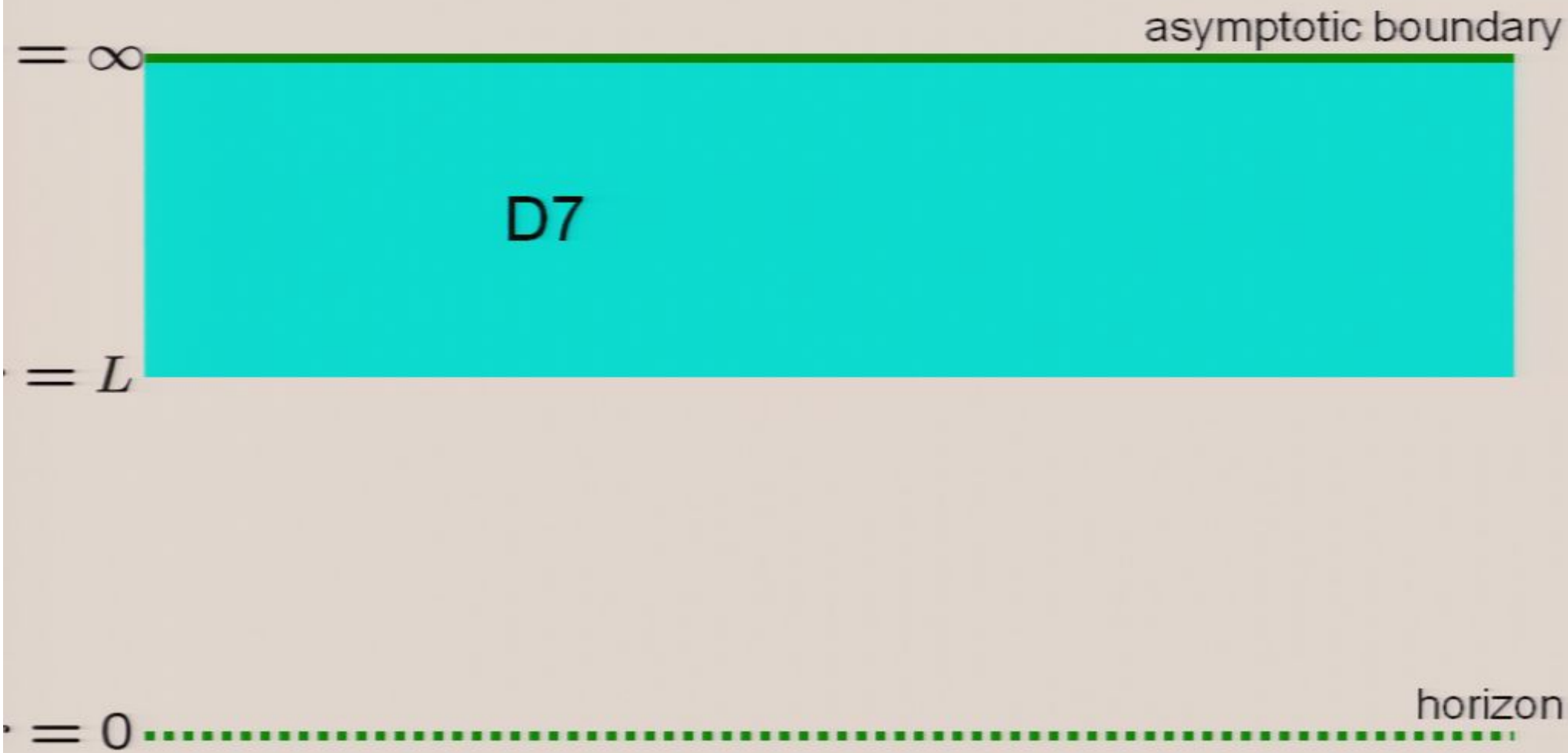

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for L sufficiently larger than r_o, D7 smoothly closes at finite r

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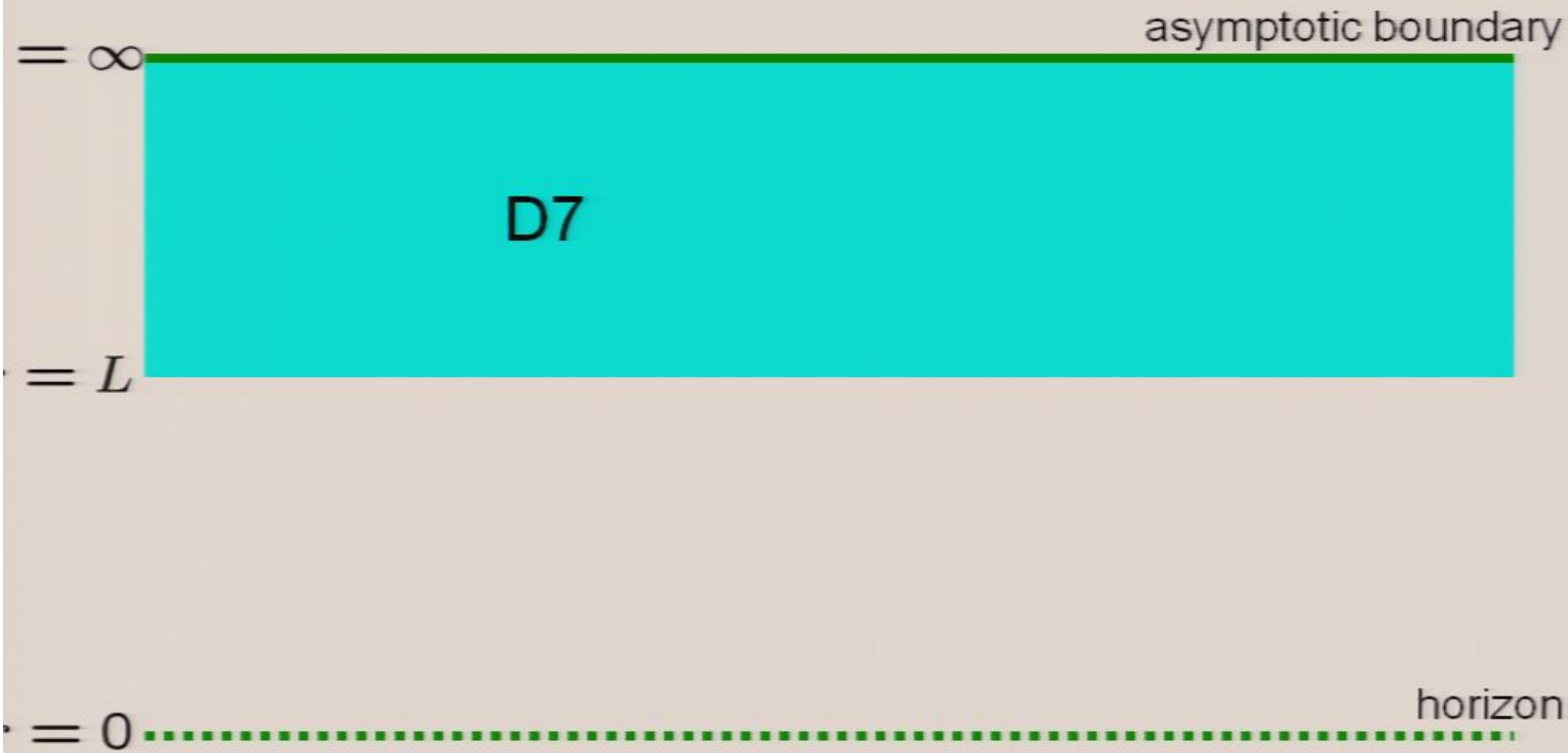

Gauge/Gravity thermodynamics with probe branes:

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for smaller L/r_0, D7 falls into the black hole horizon

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Expect to see a phase transition!

Witten; .....

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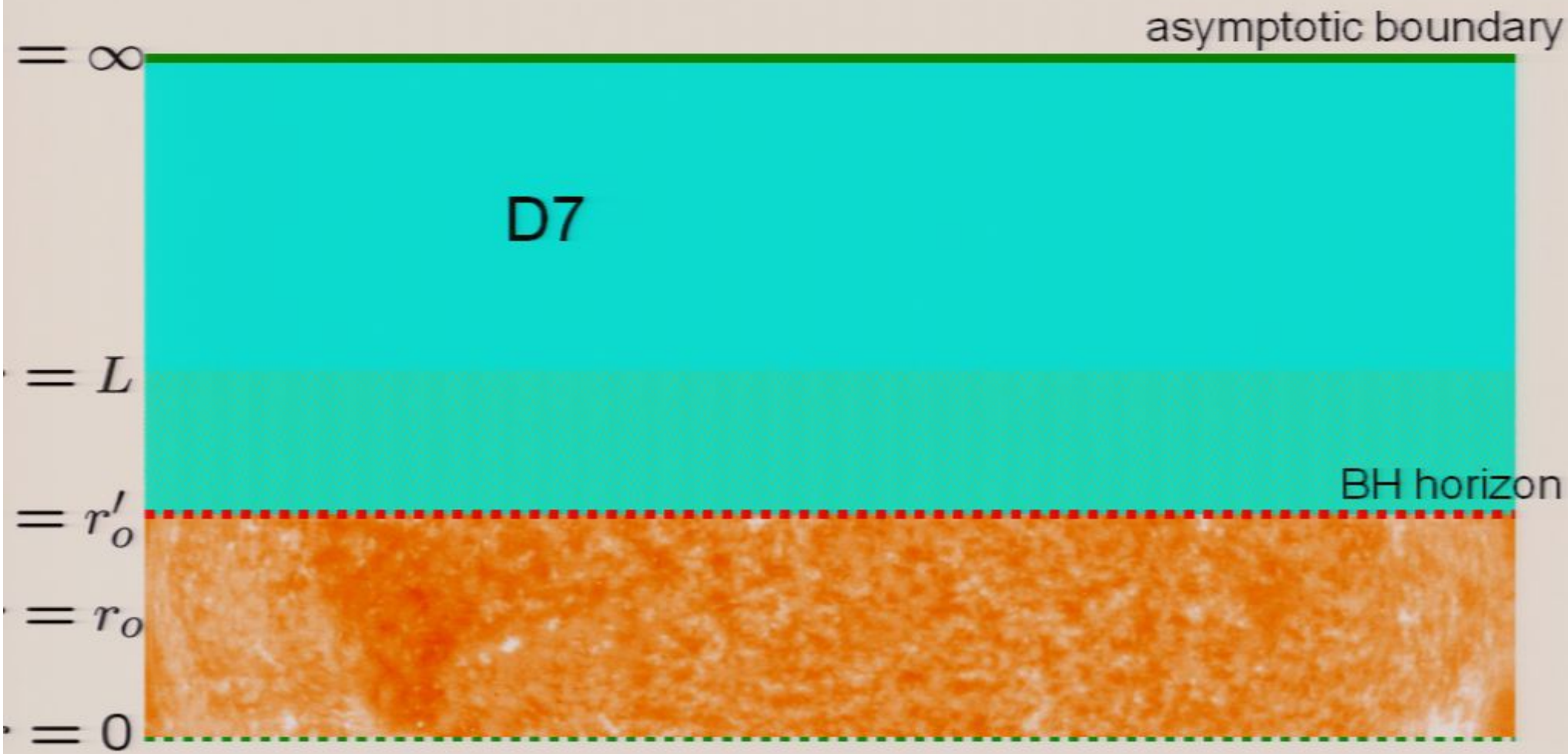

for smaller L/r_0, D7 falls into the black hole horizon

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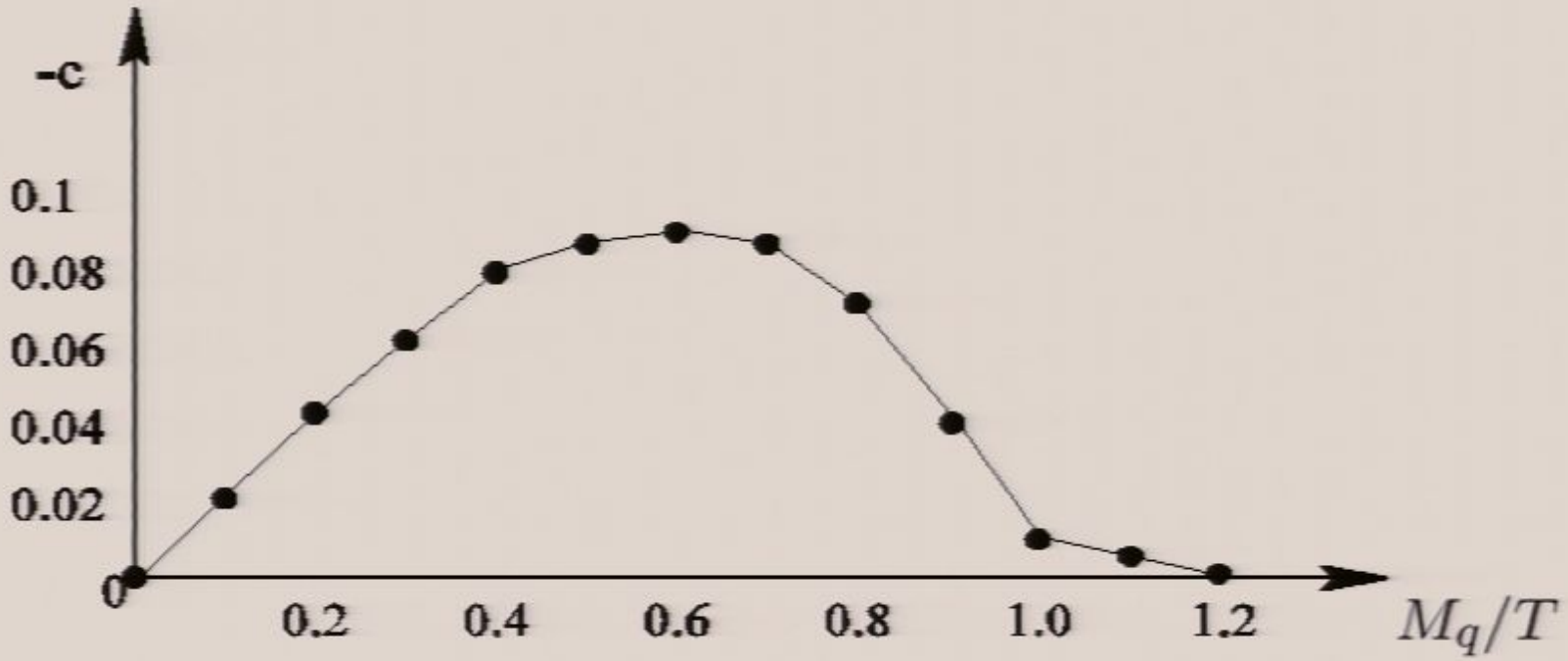
these dominate over quantum effects, eg, Hawking radiation, $\frac{1}{N_c^2}$

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

Thermal D3/D7 System:

Quark condensate $\langle \tilde{\psi}\psi \rangle$ versus quark mass M_q/T



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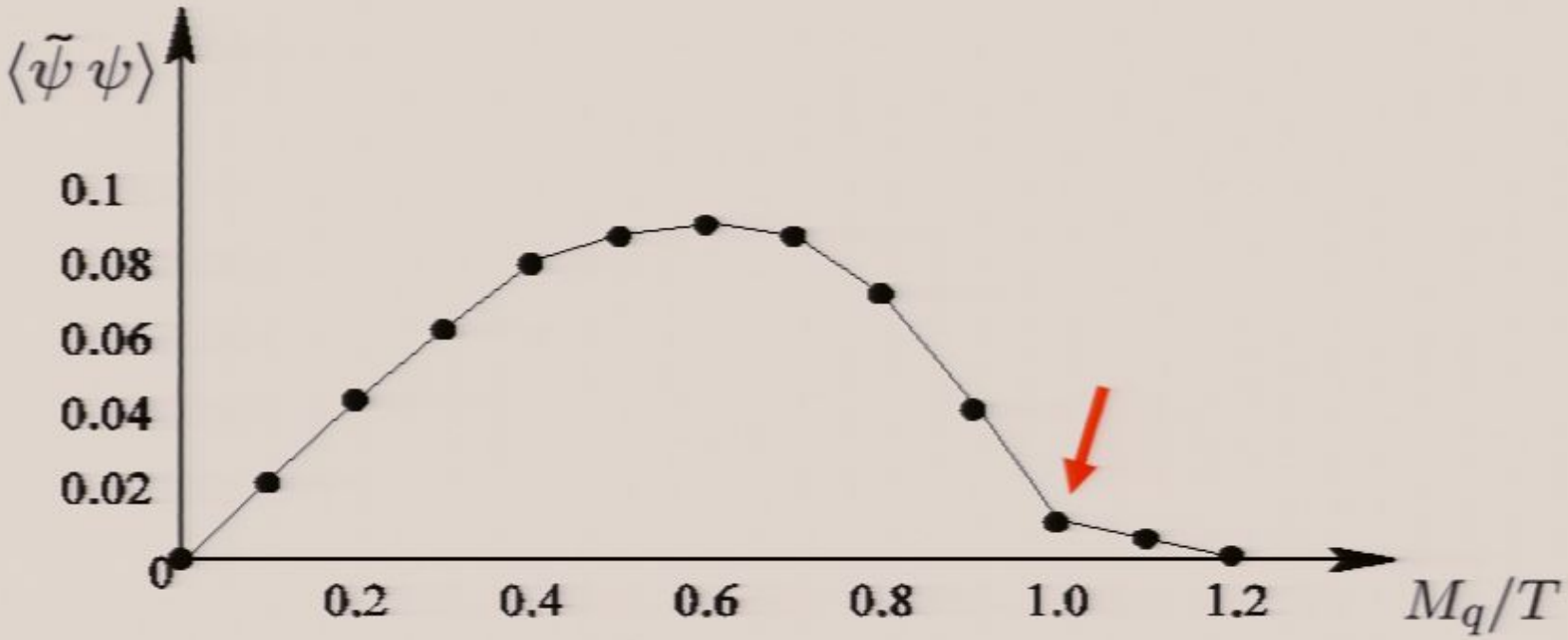

third-order transition? – needs refinement

Kirsch PhD thesis (hep-th/0406274)

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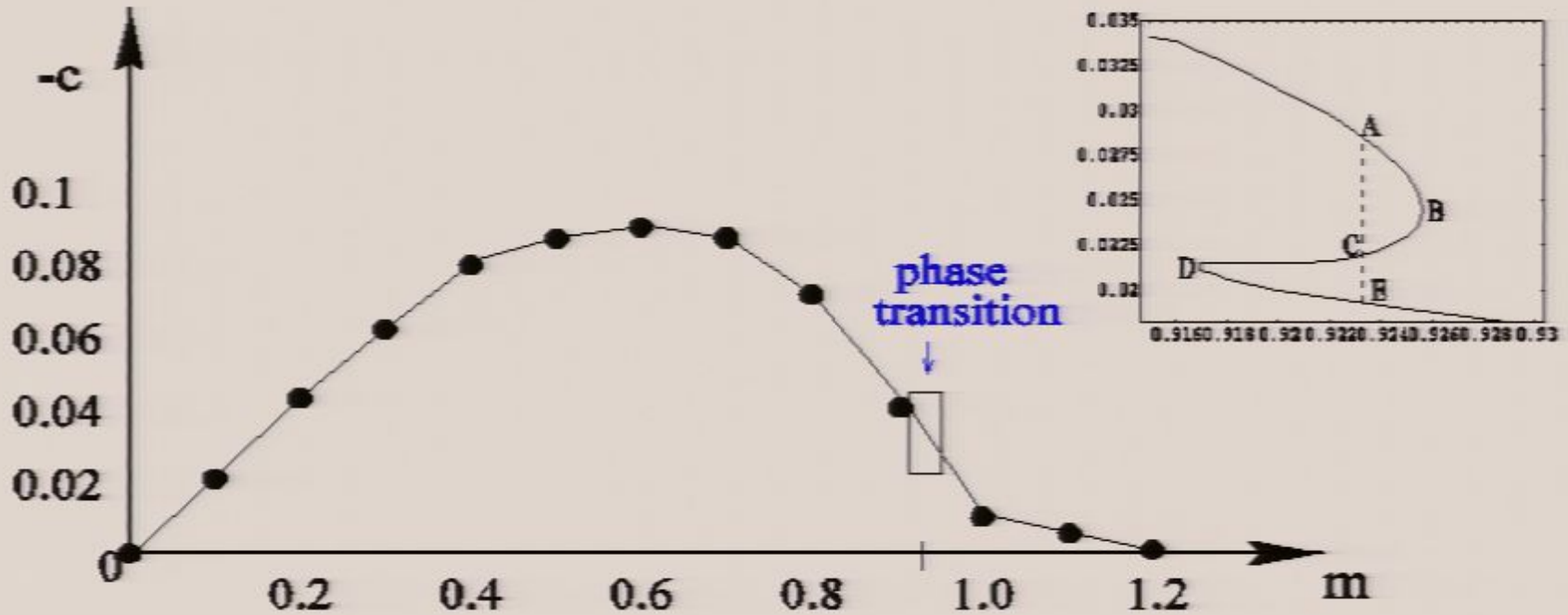
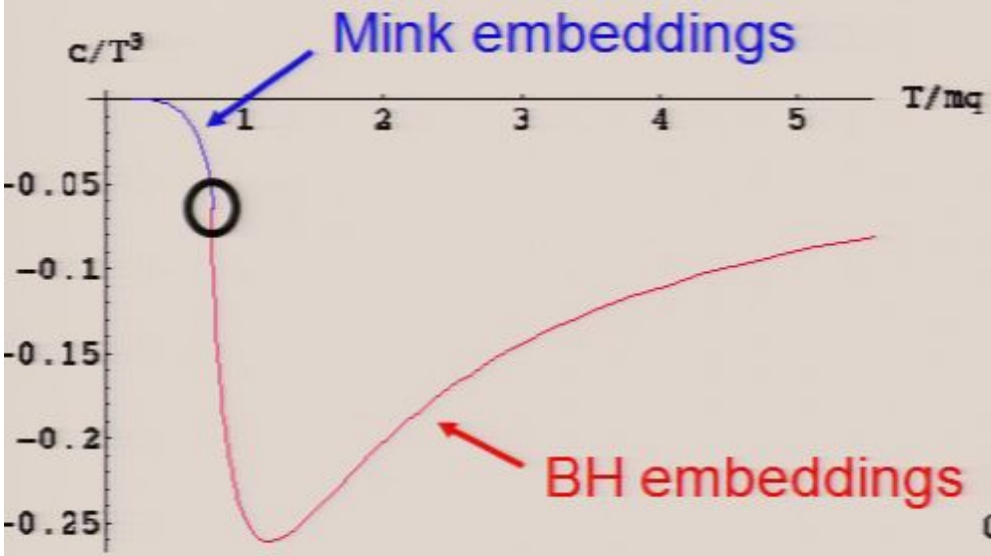
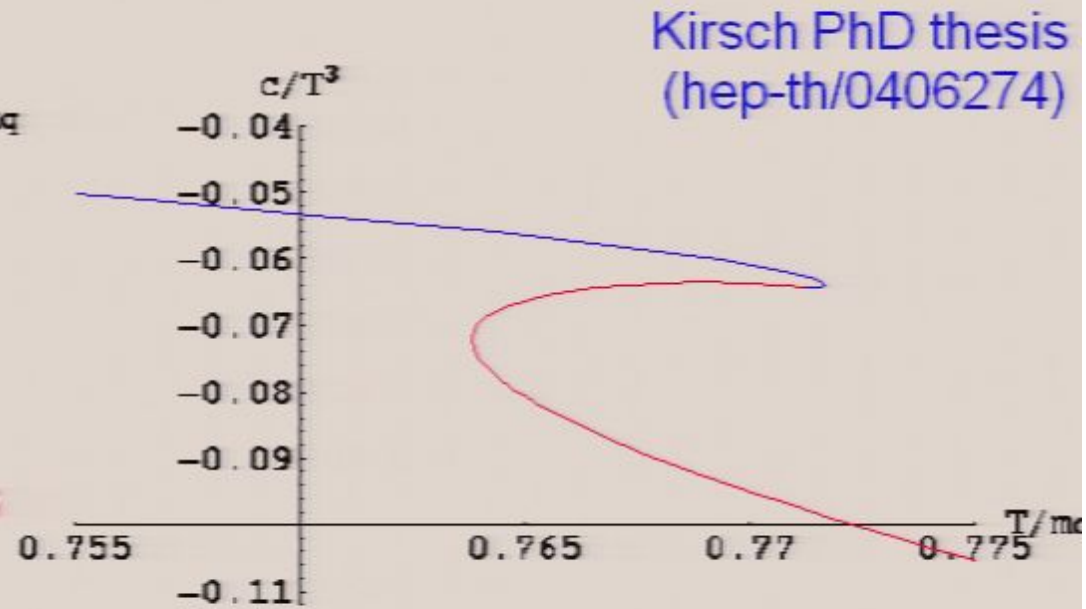


Phases do not join "smoothly" rather spiral in on critical solution





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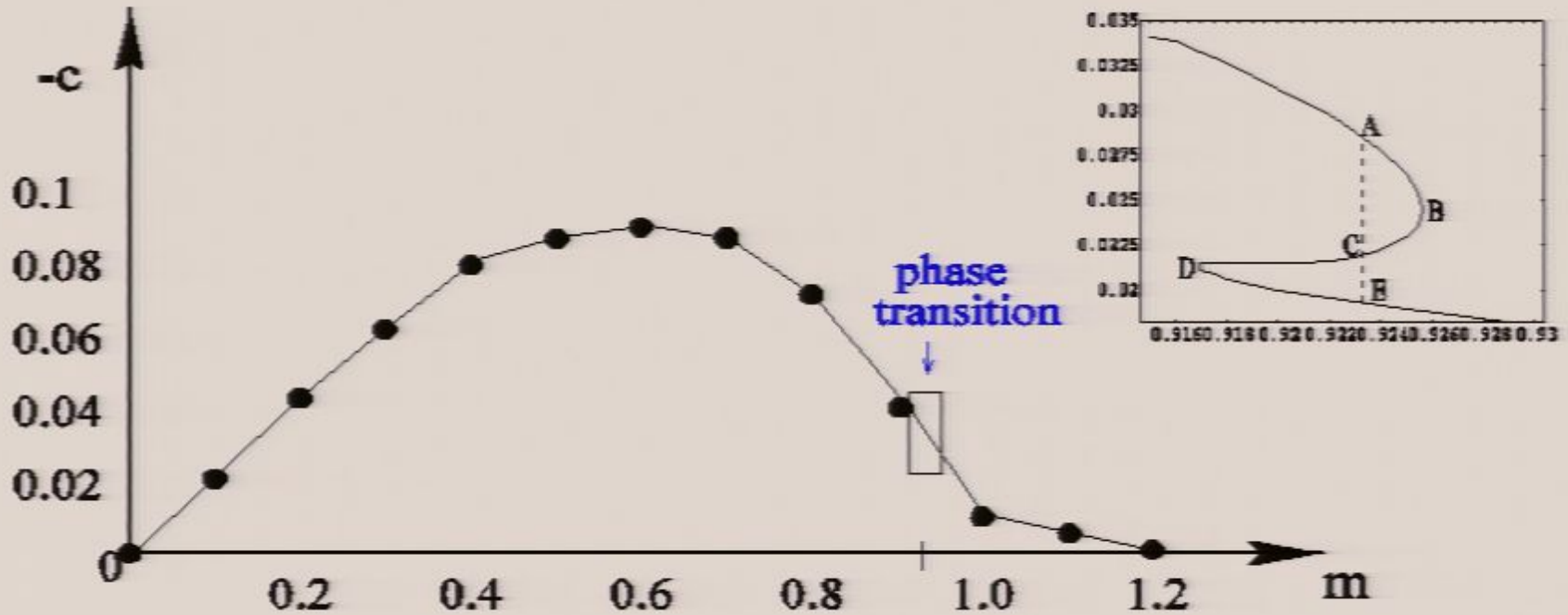

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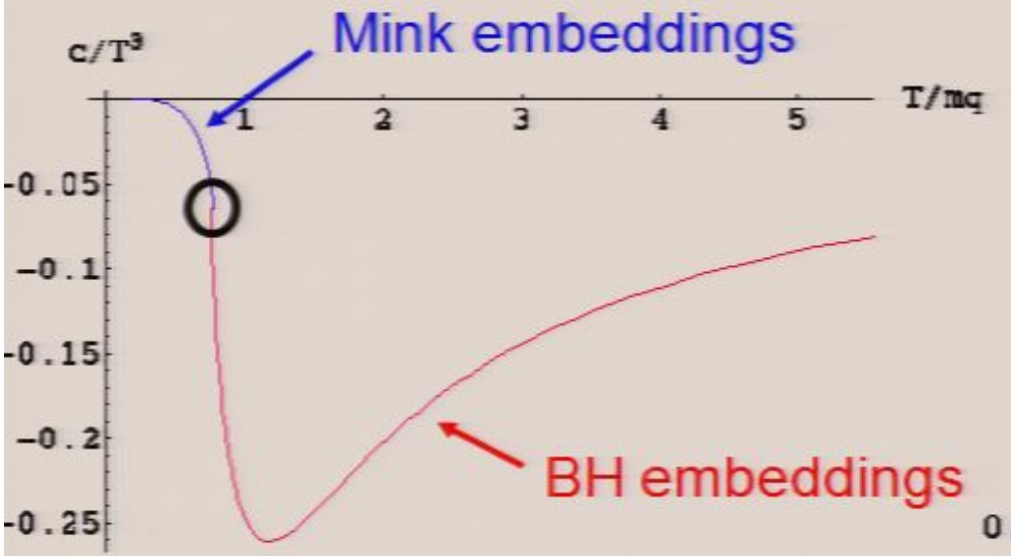

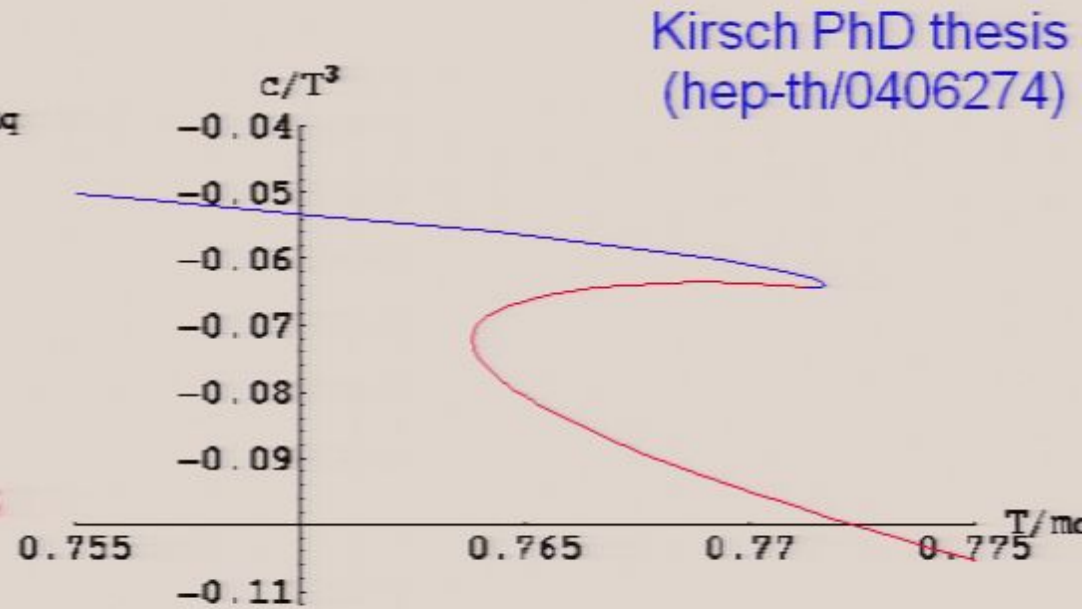

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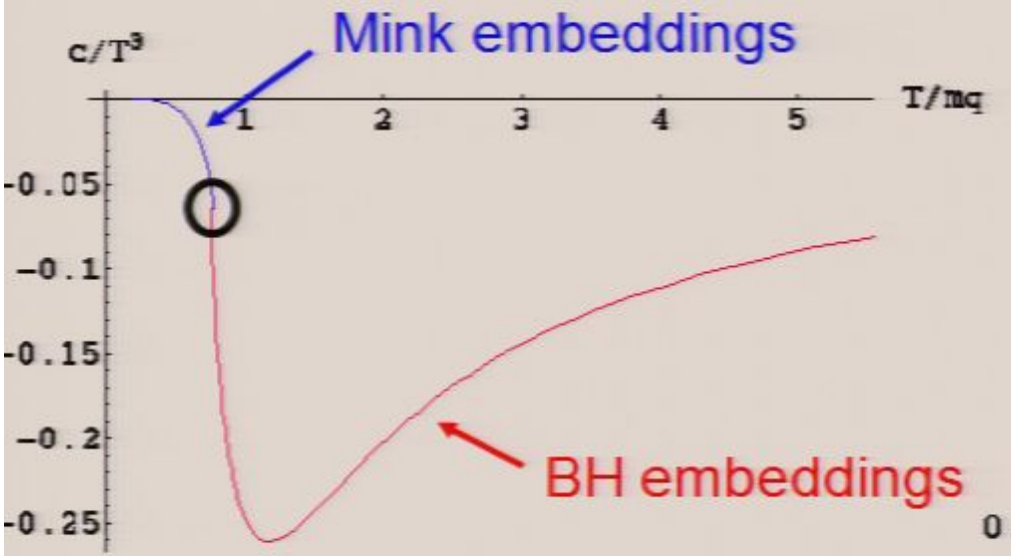

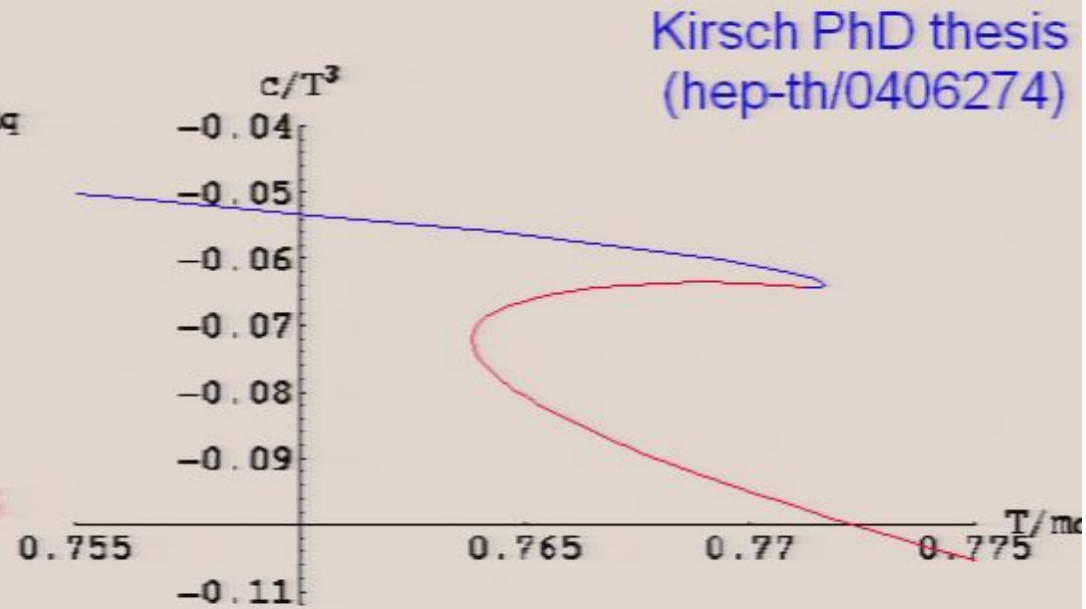

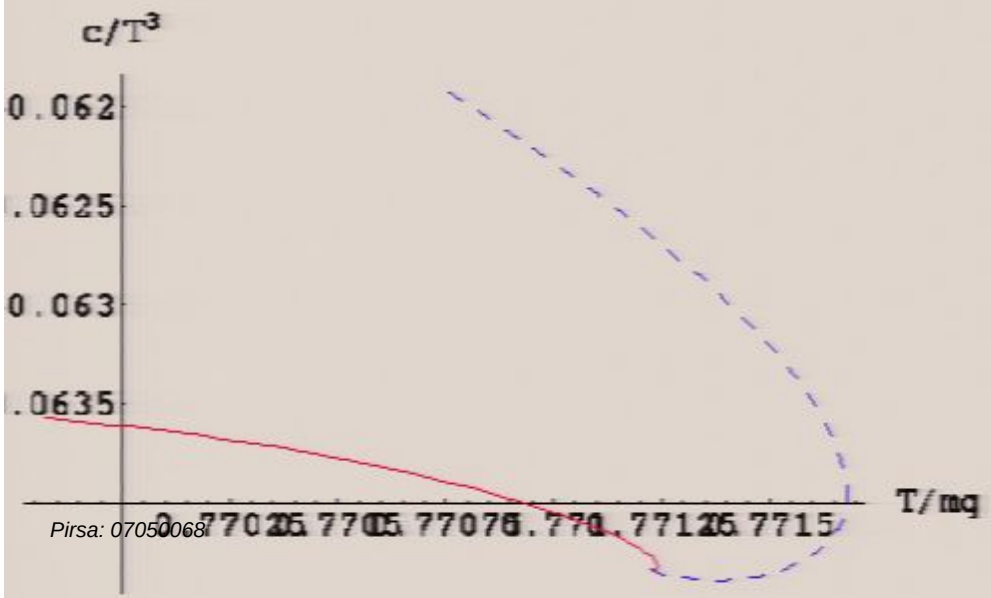

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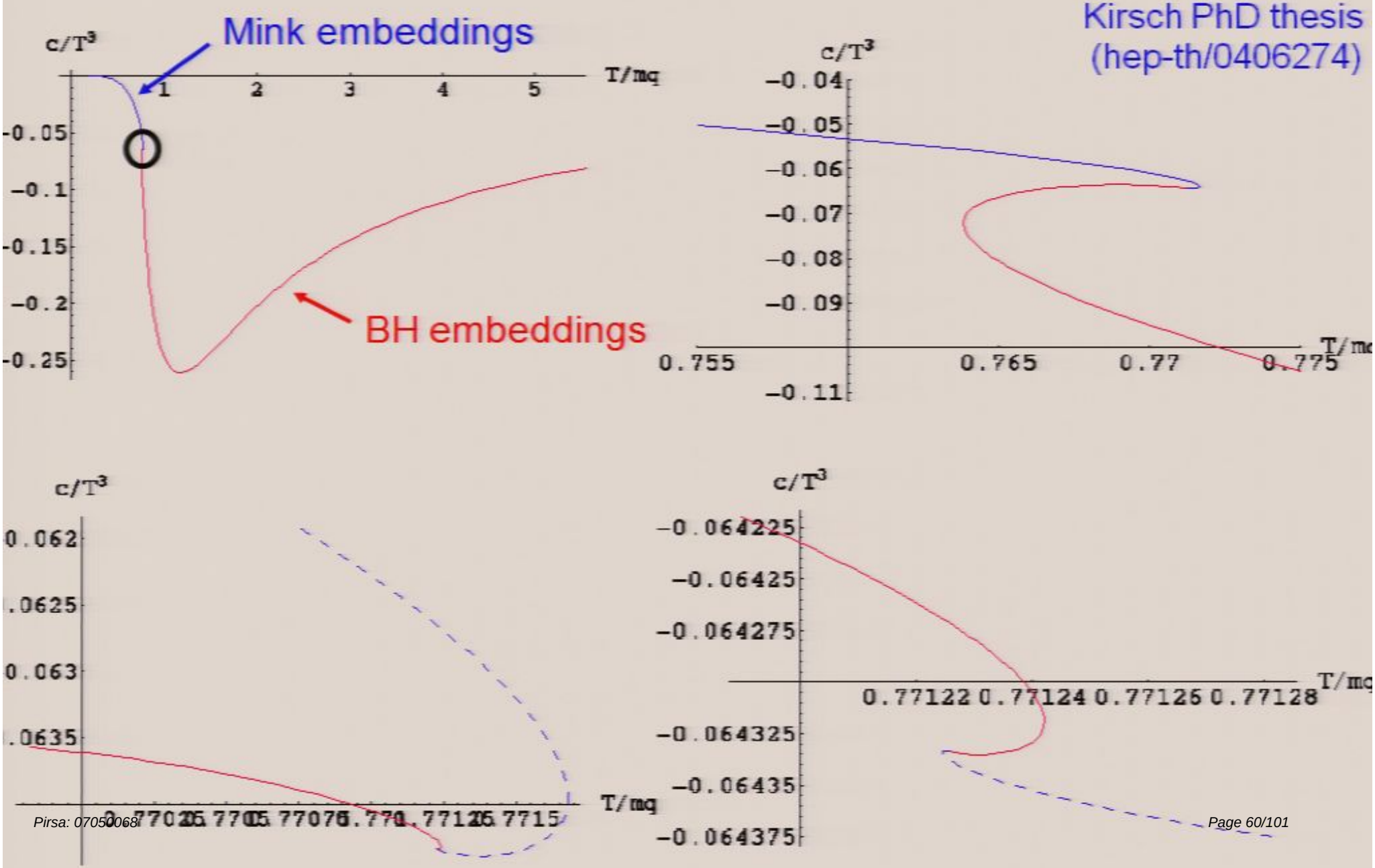
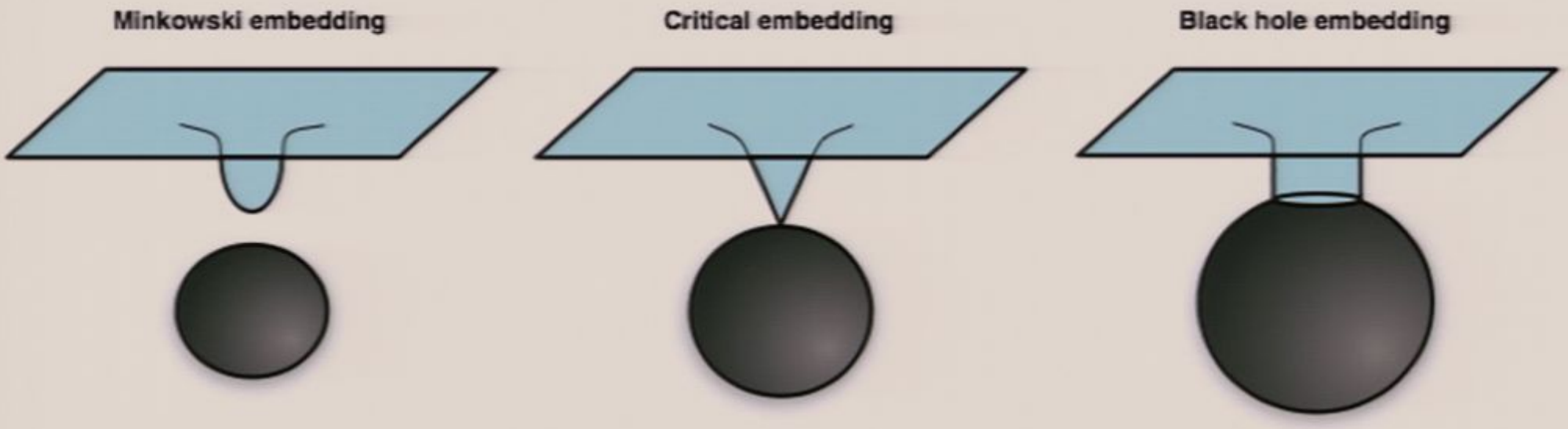


approach to critical embedding → self-similar behaviour



Frolov, Larsen and Christensen (hep-th/9811148)
Frolov (gr-qc/0604114)

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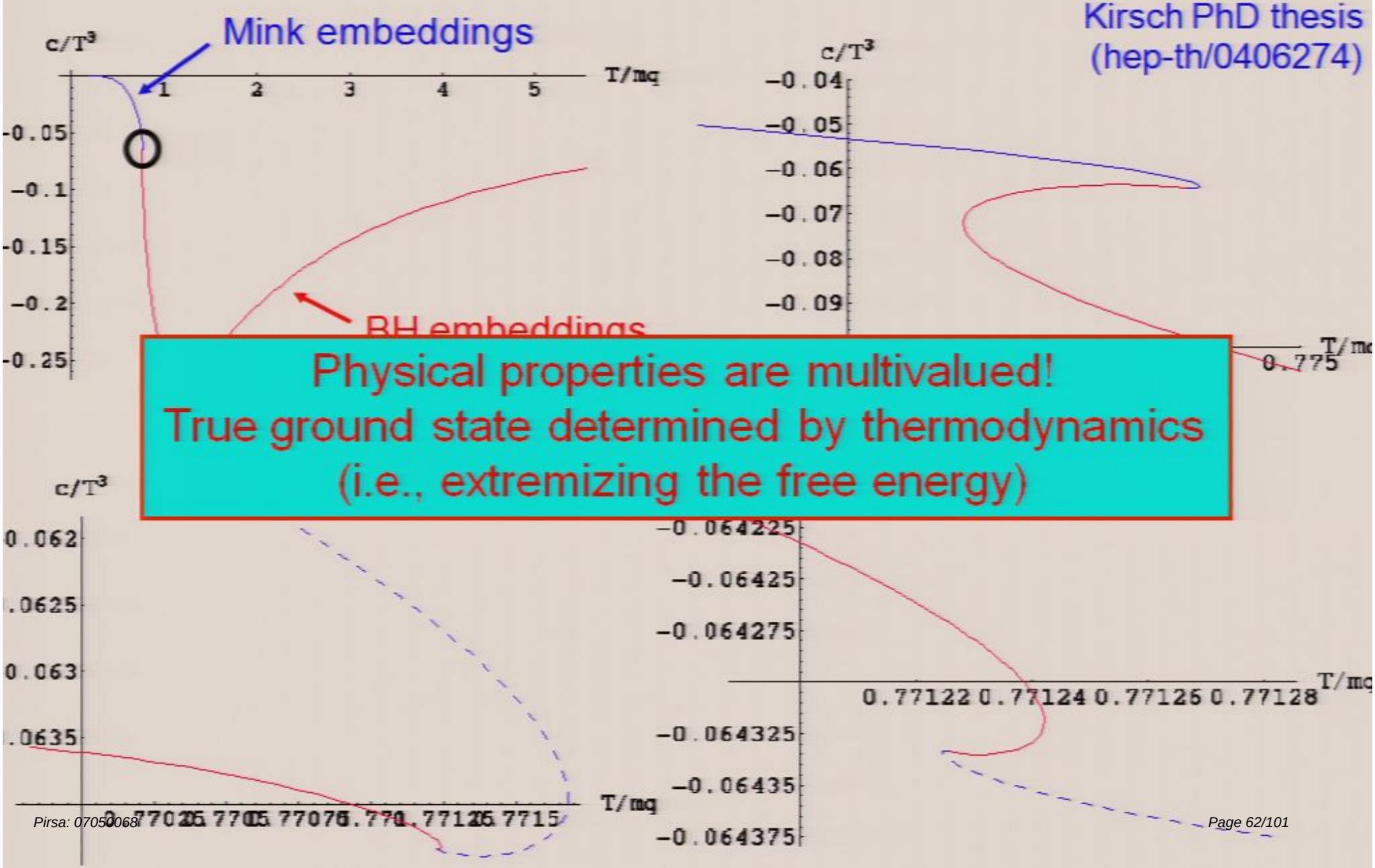
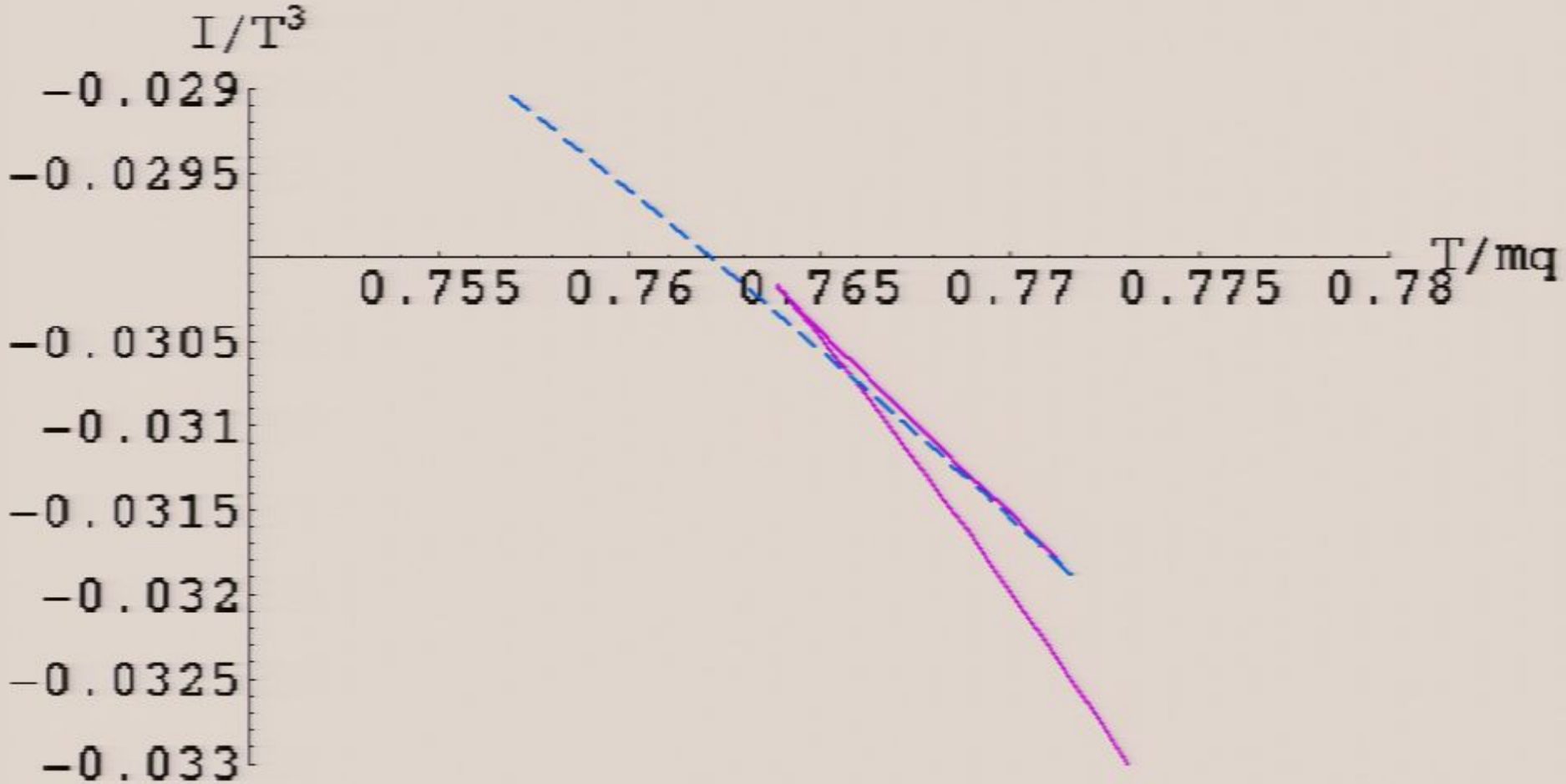


Physical properties are multivalued!
True ground state determined by thermodynamics
(i.e., extremizing the free energy)

physical properties of thermal system are multi-valued → minimizing free energy determines physical configuration: $F = I_{D7}/V_x\beta$



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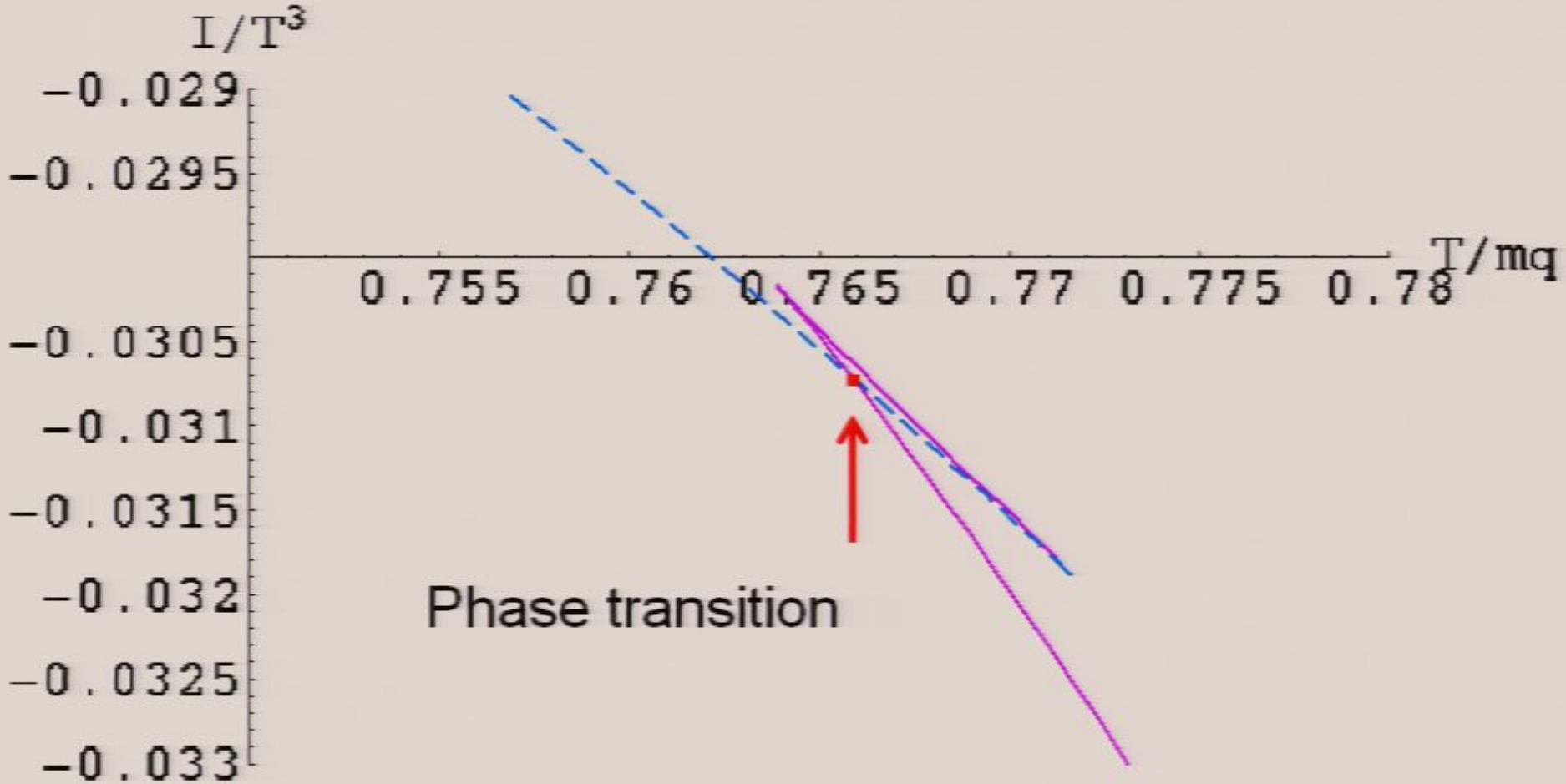

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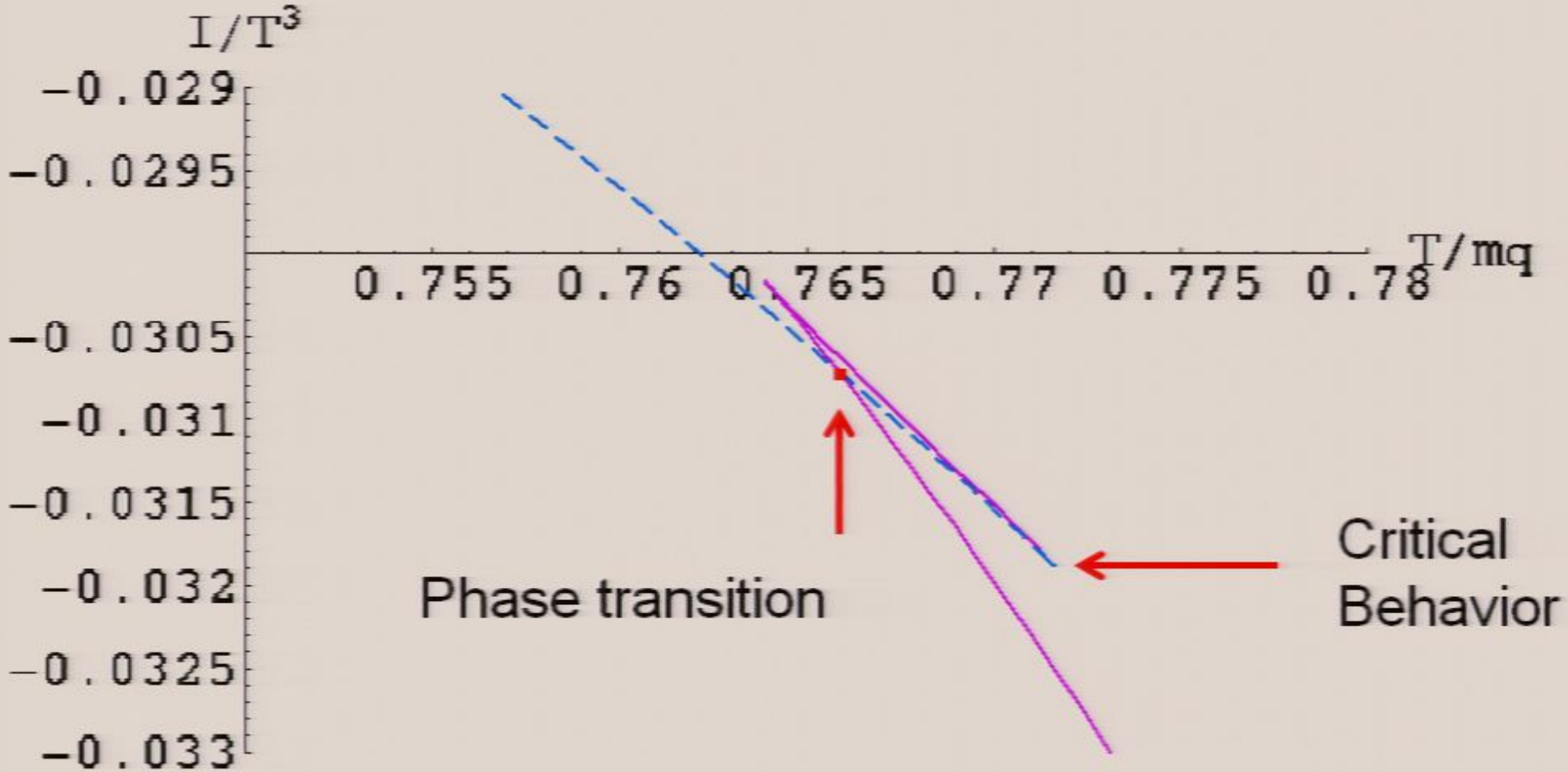
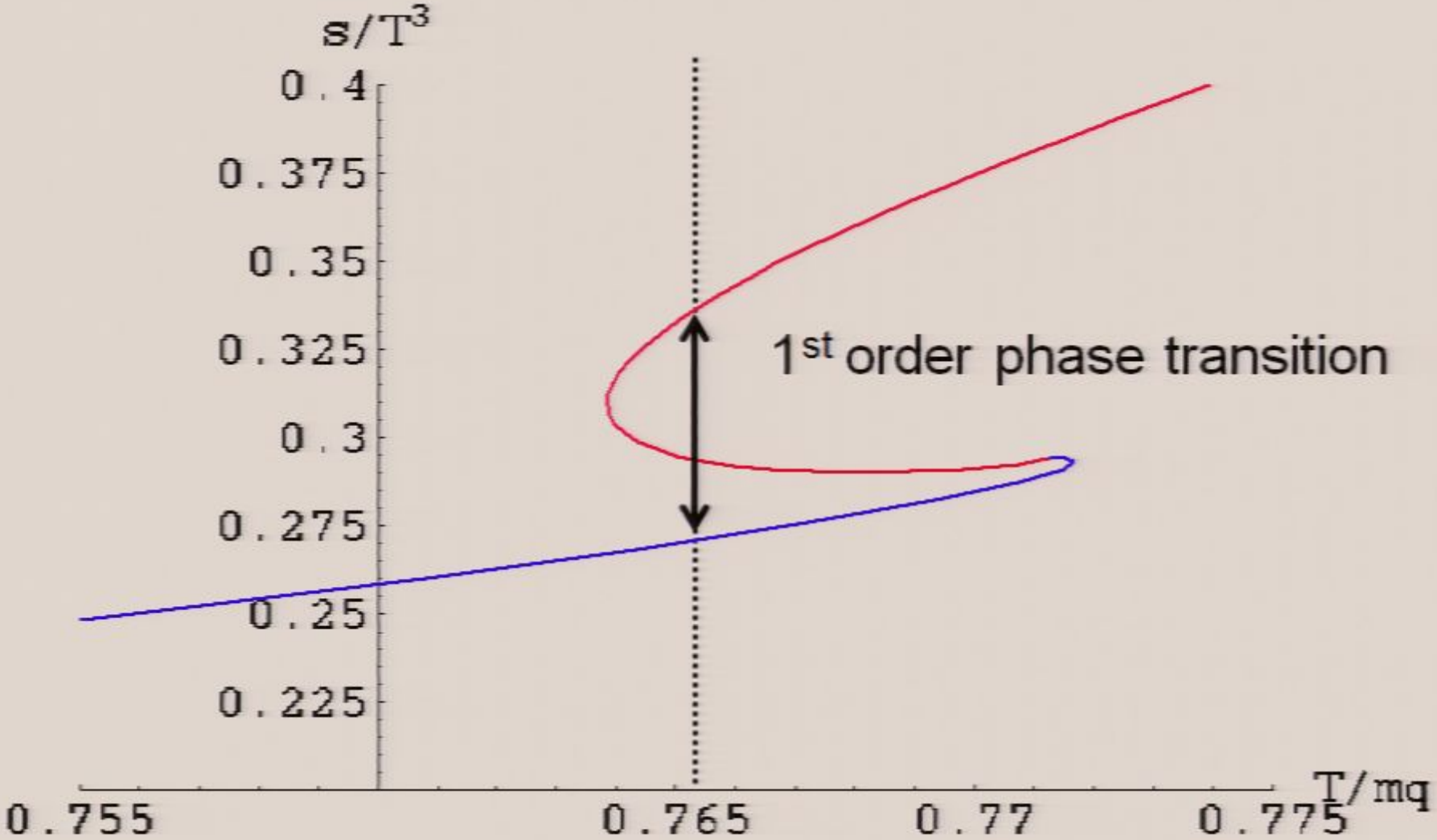


Brane entropy:

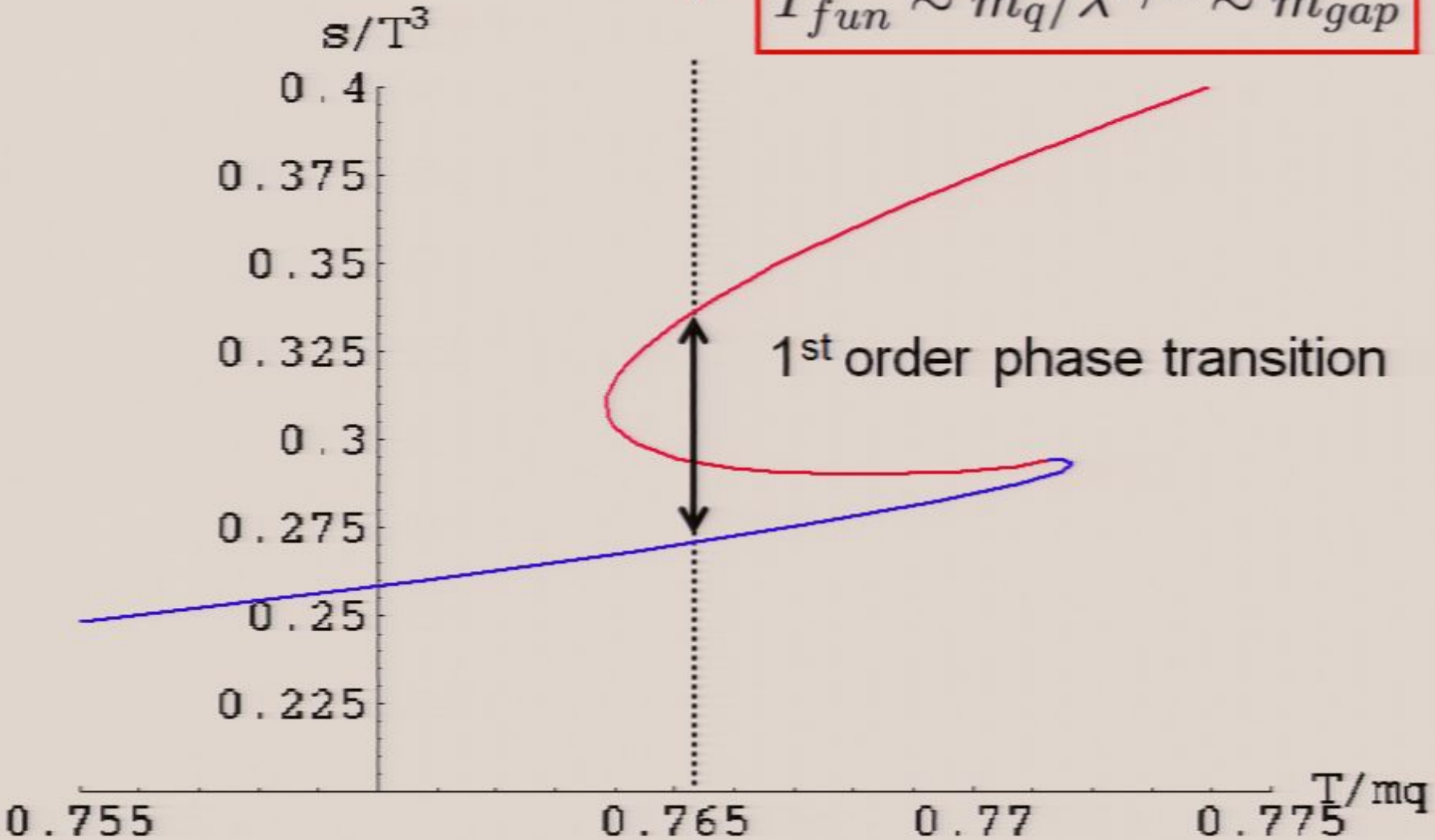


1st order because of multivalued self-similar behaviour

Brane entropy:

Transition temperature:

$$T_{fun} \sim m_q/\lambda^{1/2} \sim m_{gap}$$



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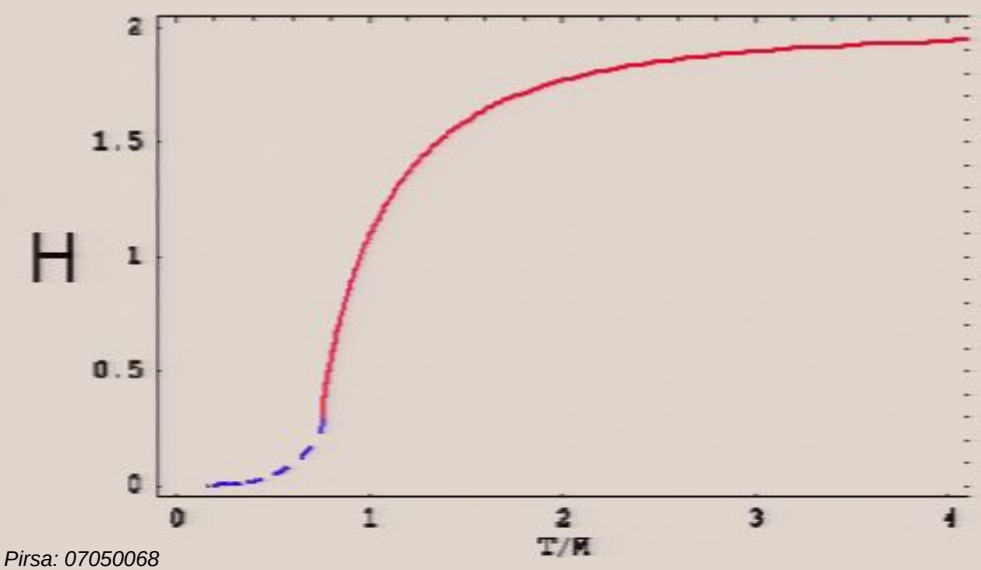

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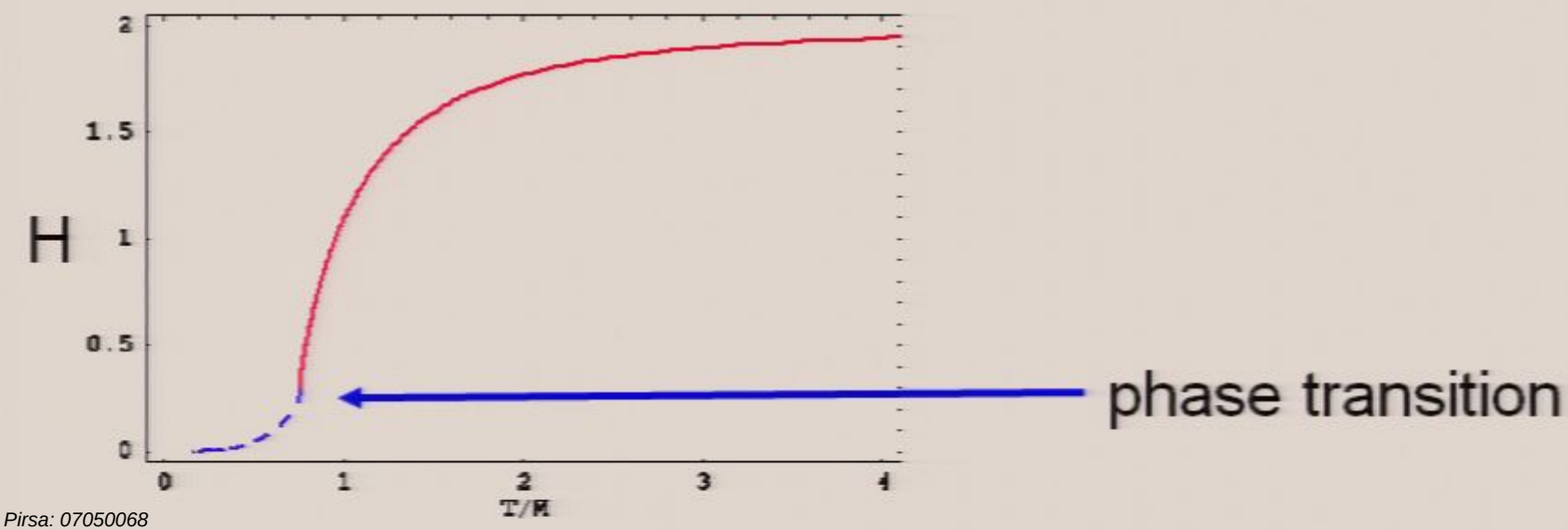

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enhanced over naïve large-N counting

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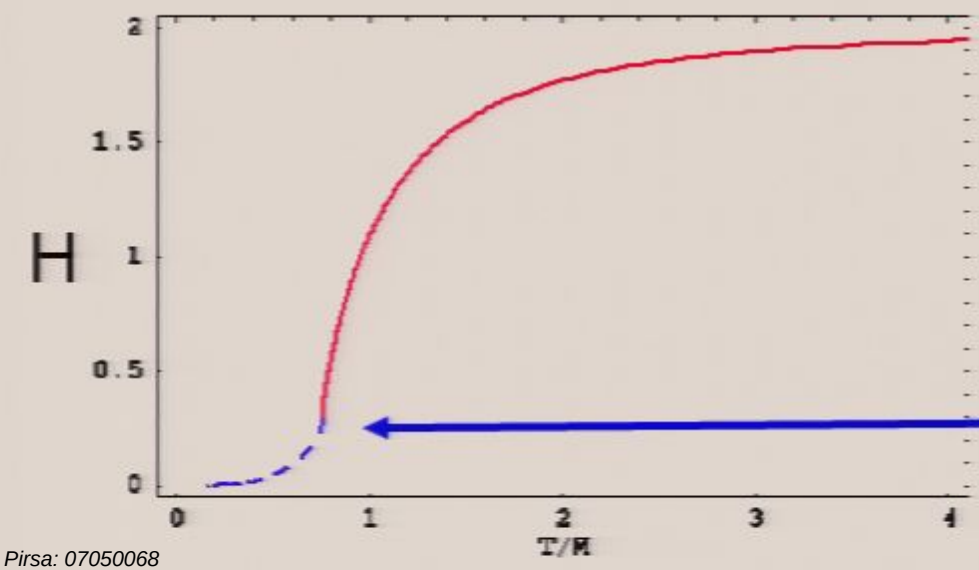
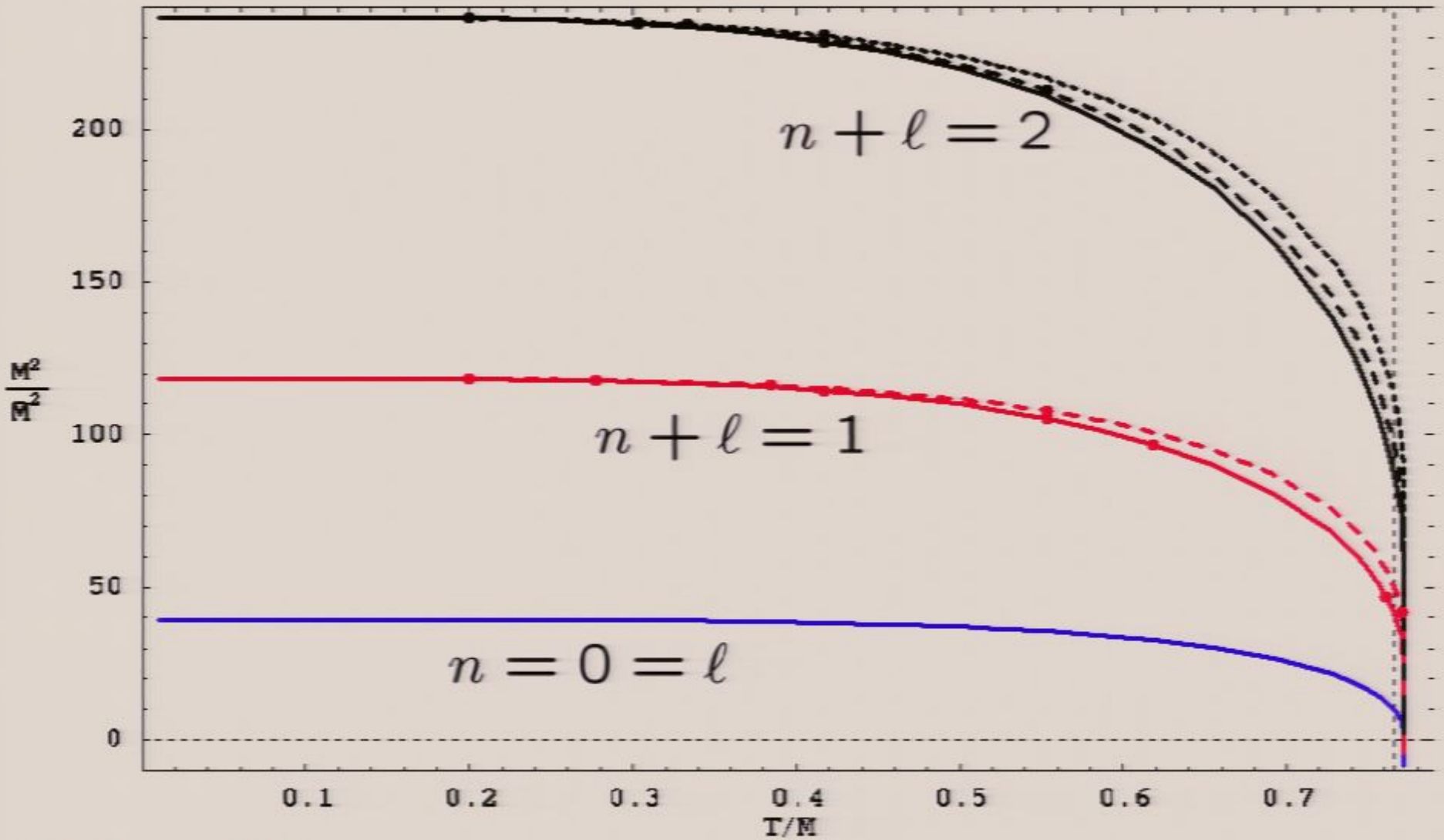


phase transition

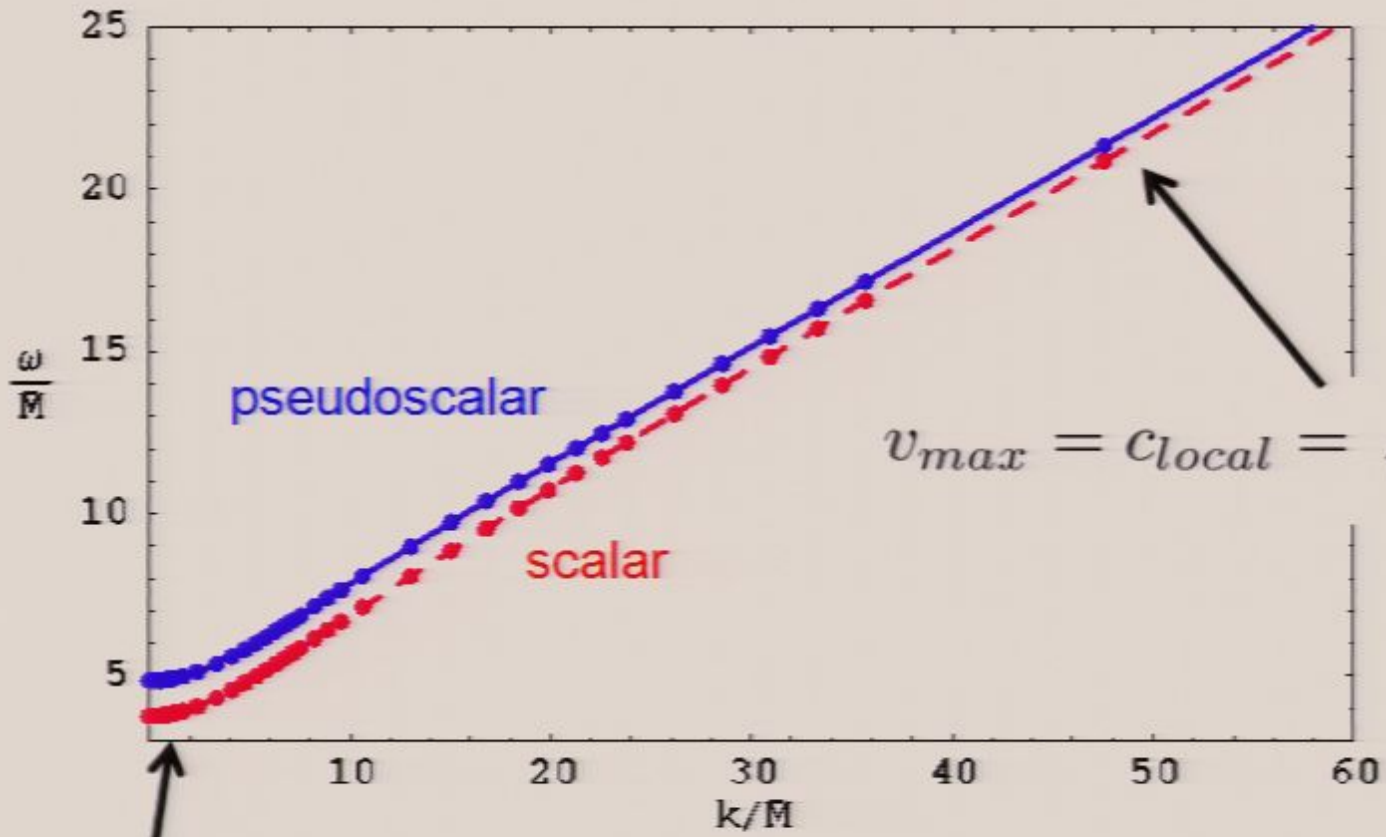
Meson spectrum: (pseudoscalars)



on Minkowski branes, spectrum remains discrete and stable, but as T grows, masses decrease & degeneracy with $n+\ell$ broken

Mesons in Motion:

(see also: Liu, Rajagopal, …)



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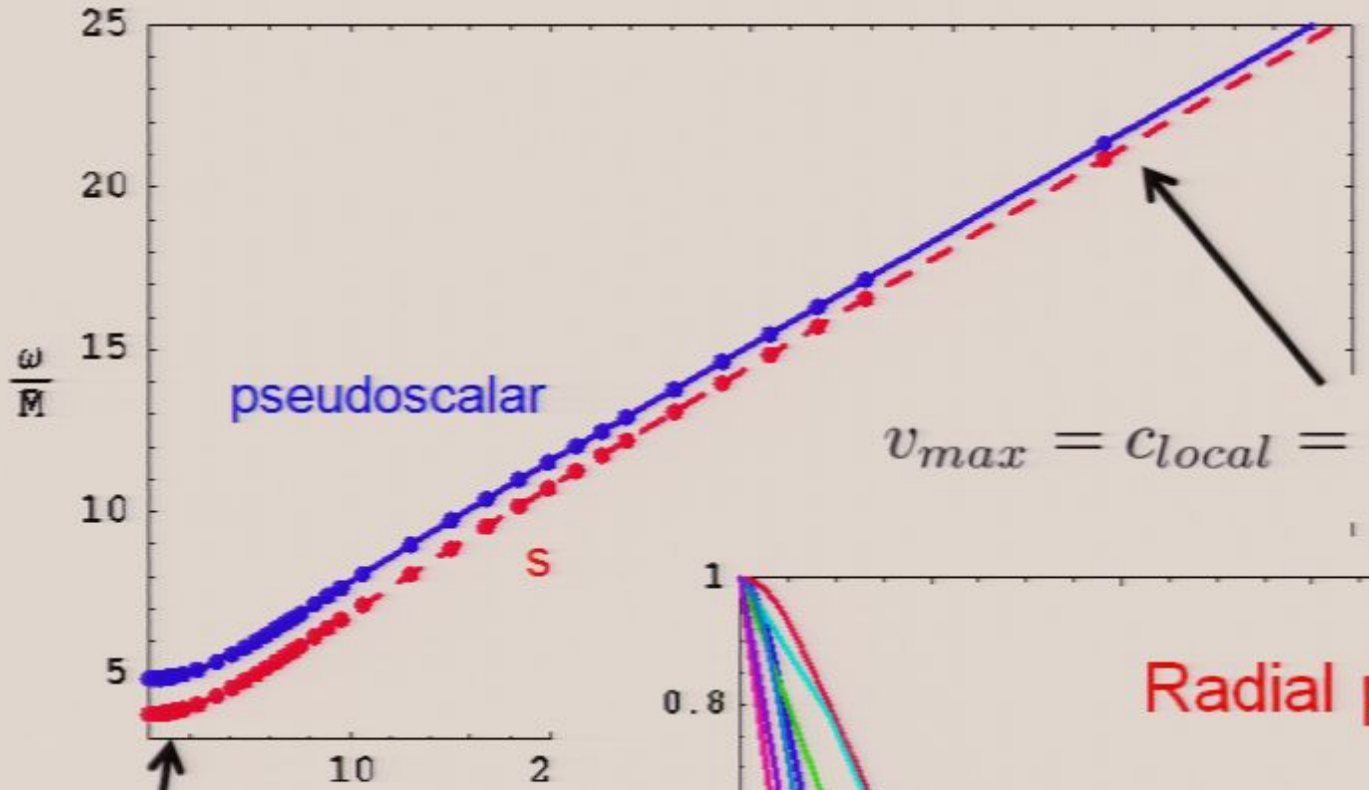

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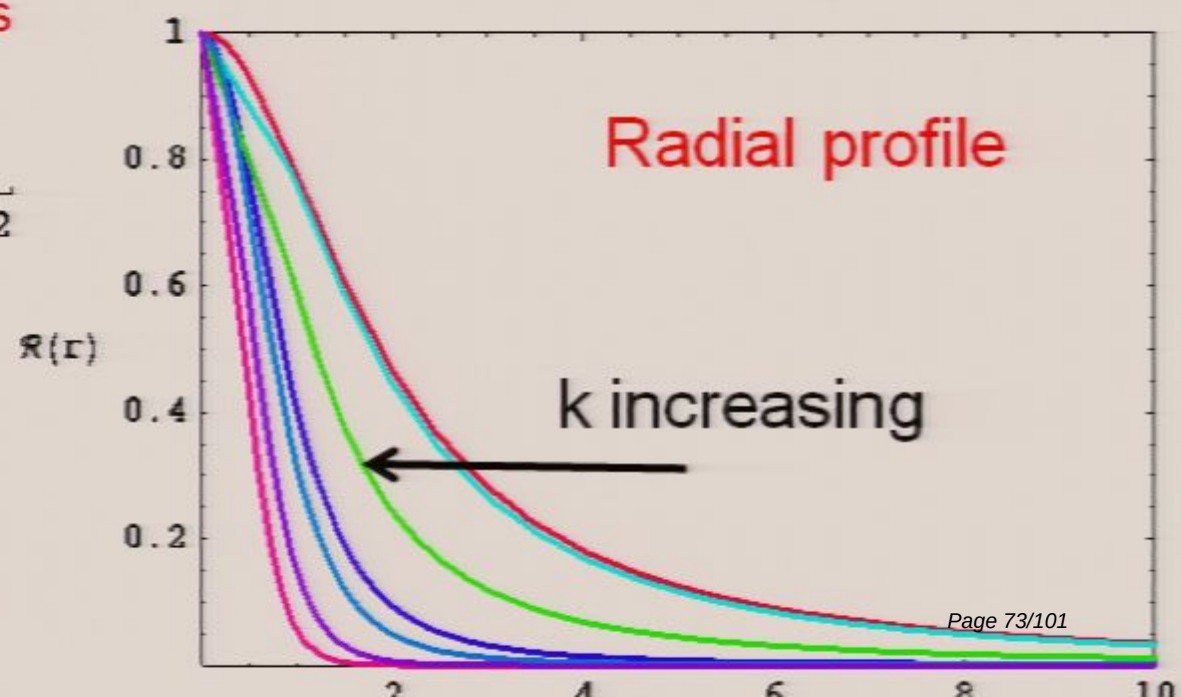

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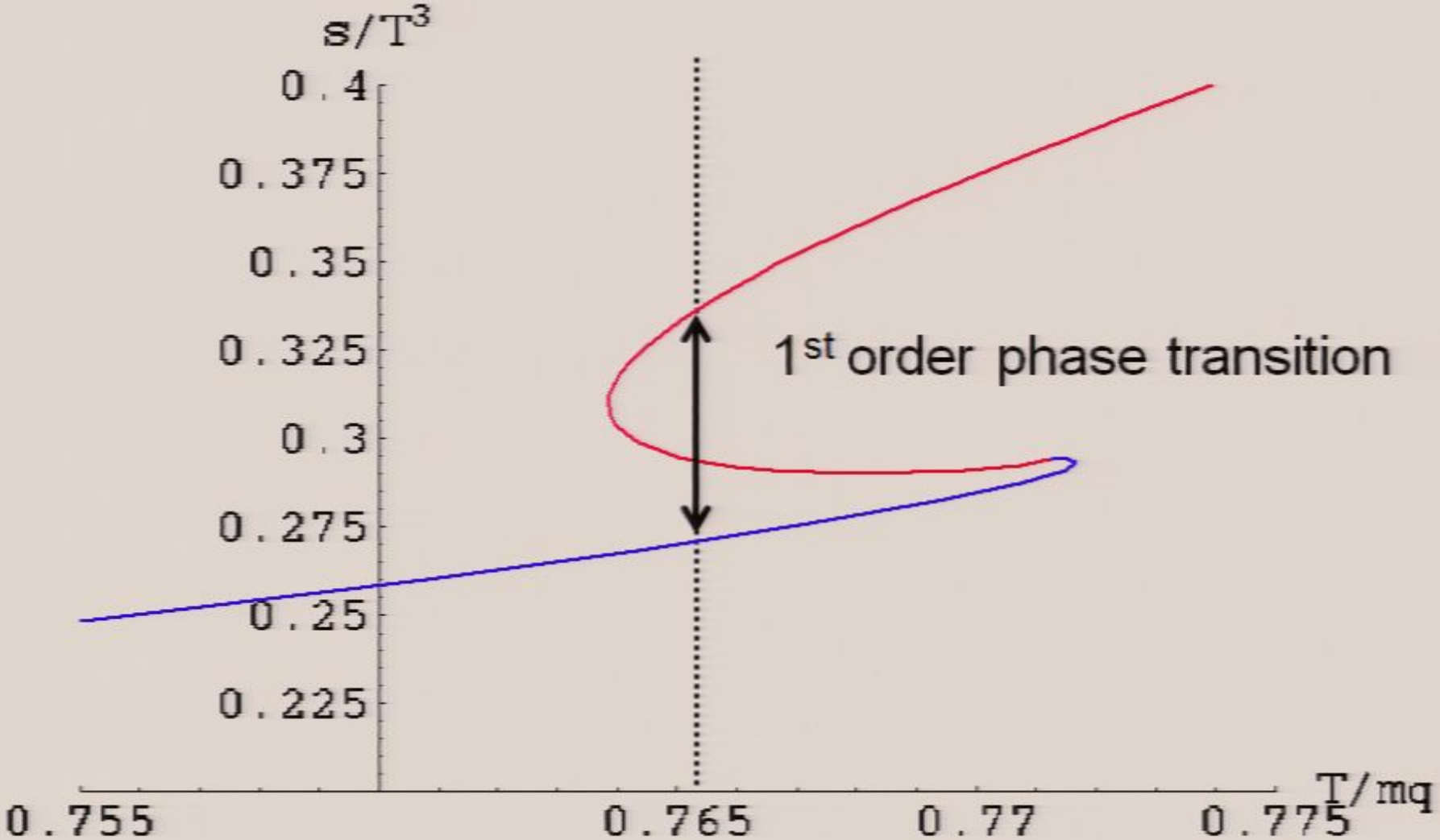

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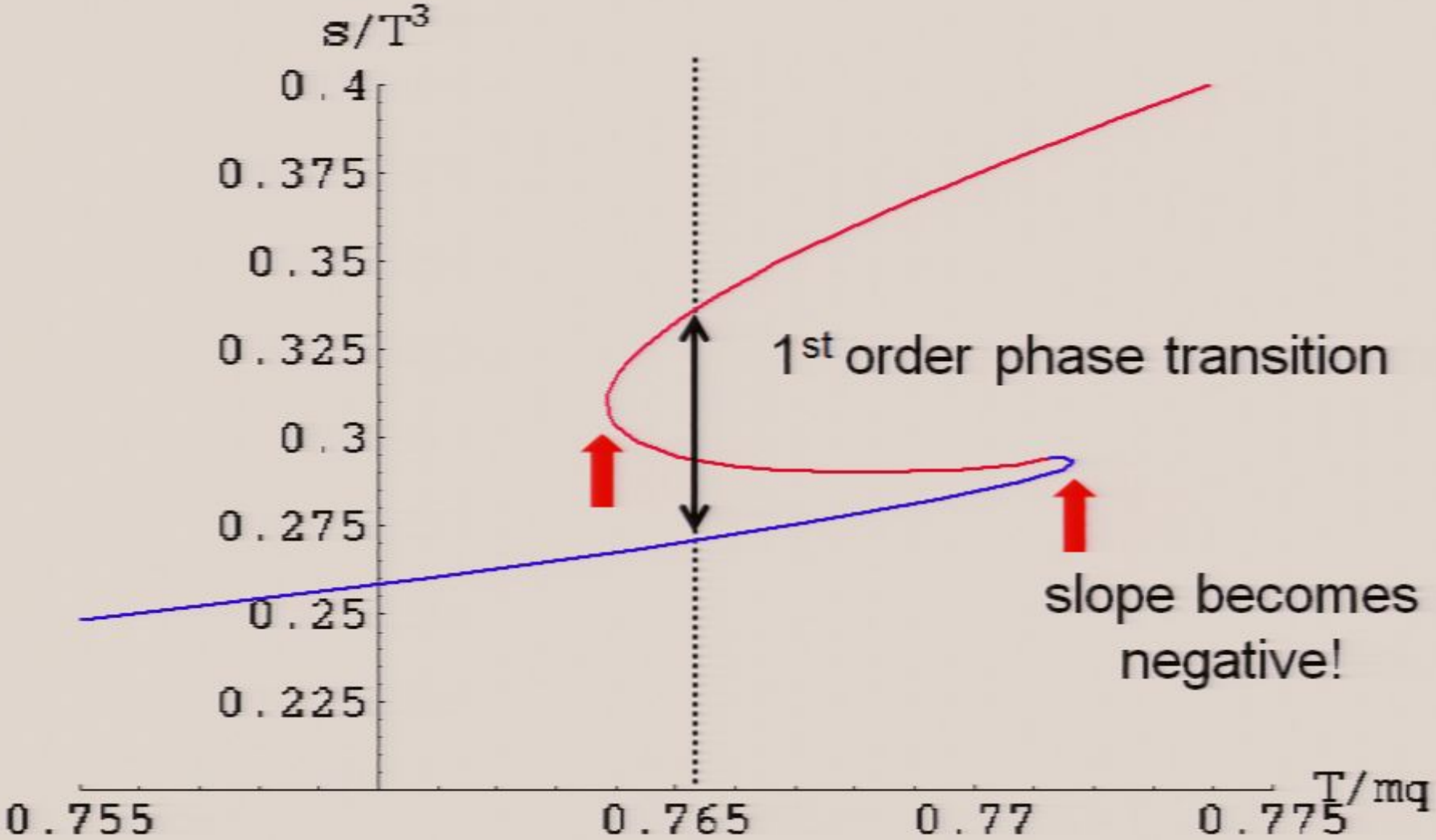
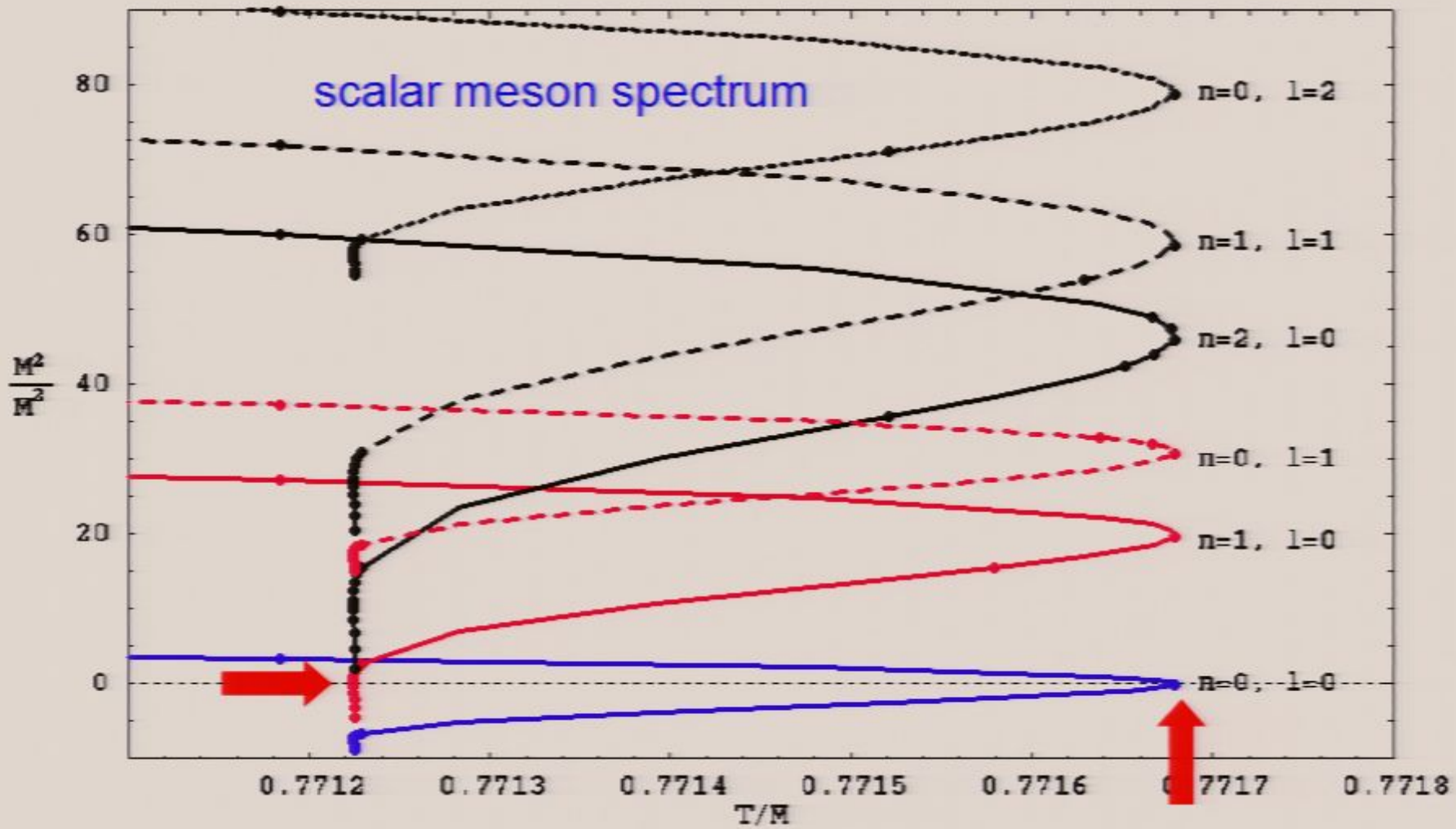


hence in spiral region, branes must be unstable!

Stability: Thermal instability can be seen as dynamical instability in the meson spectrum



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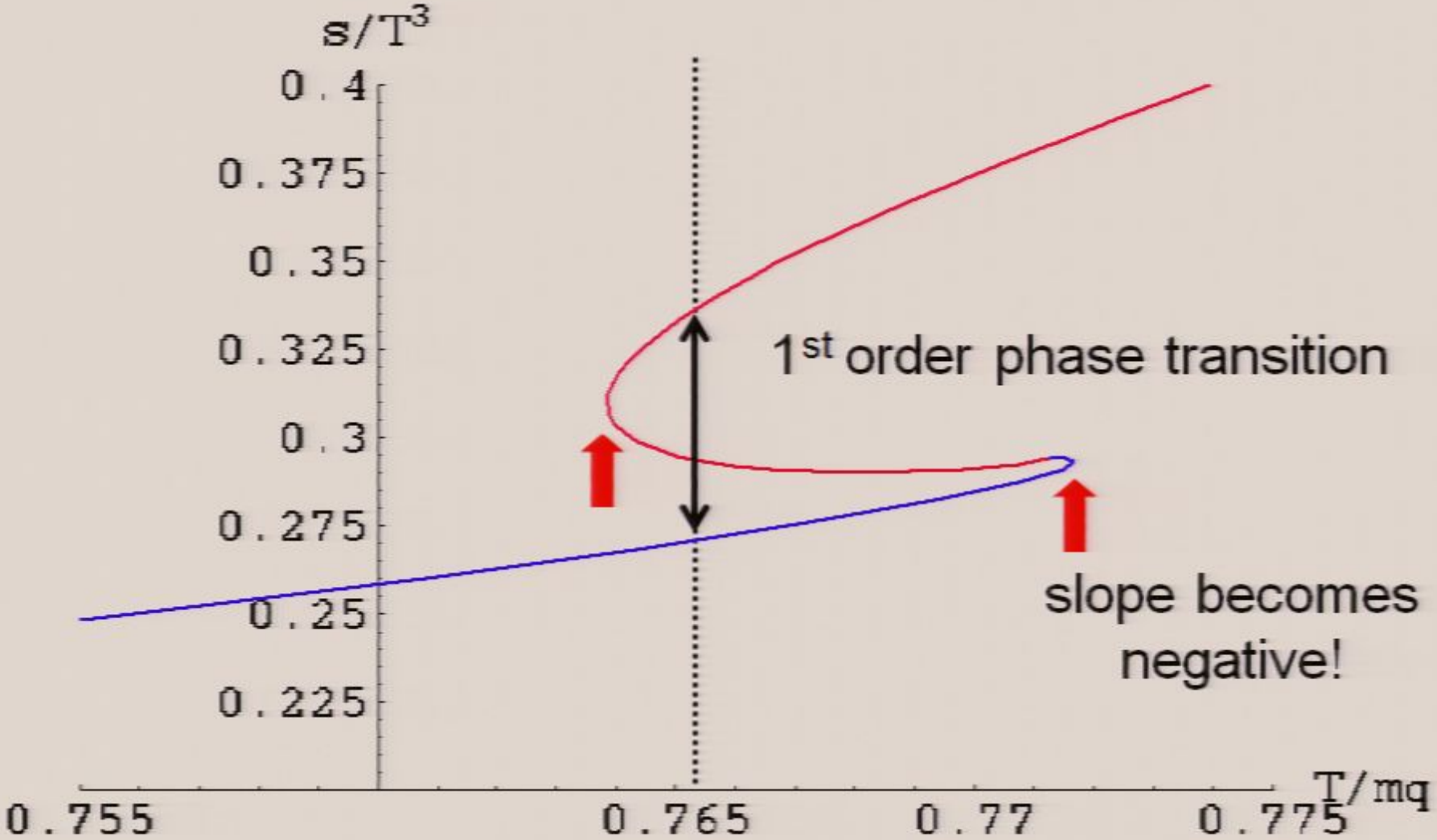

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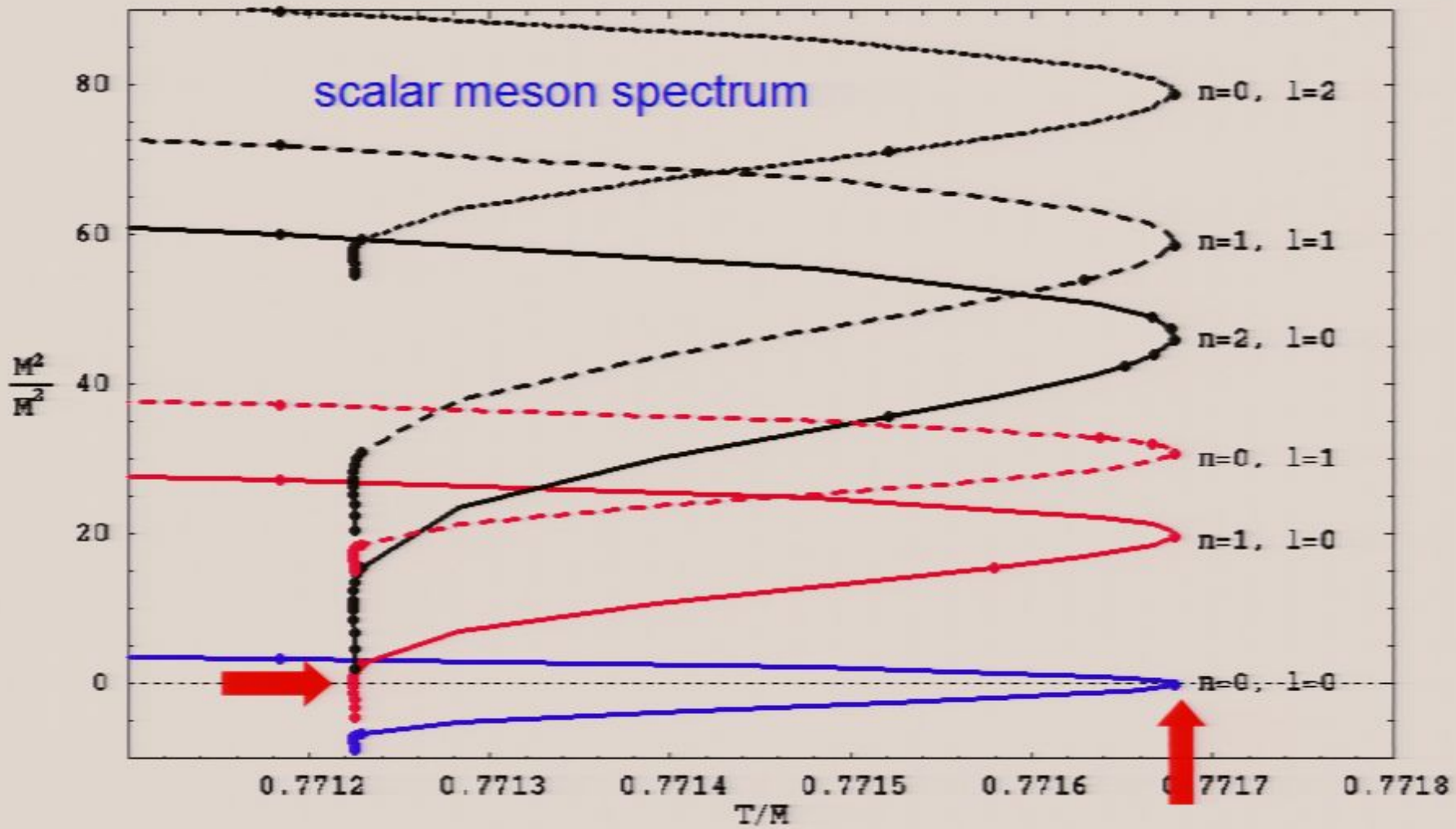

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- feature of QCD ??
- simple physical picture:

Matsui & Satz

structure functions reveal: $r \sim \lambda / M_q$ (Hong, Yoon & Strassler)

Wilson lines reveal: $L \sim 1/T$ (Rey, Theisen & Yee)

mesons dissociate: $L \sim r \longrightarrow T \sim M_q / \lambda$

Outline:

1. Gauge/Gravity duality with fundamental fields
   $\longrightarrow$ add probe branes

2. Probe branes in thermal backgrounds
   $\longrightarrow$ first-order phase transition;
   "mesons melting"

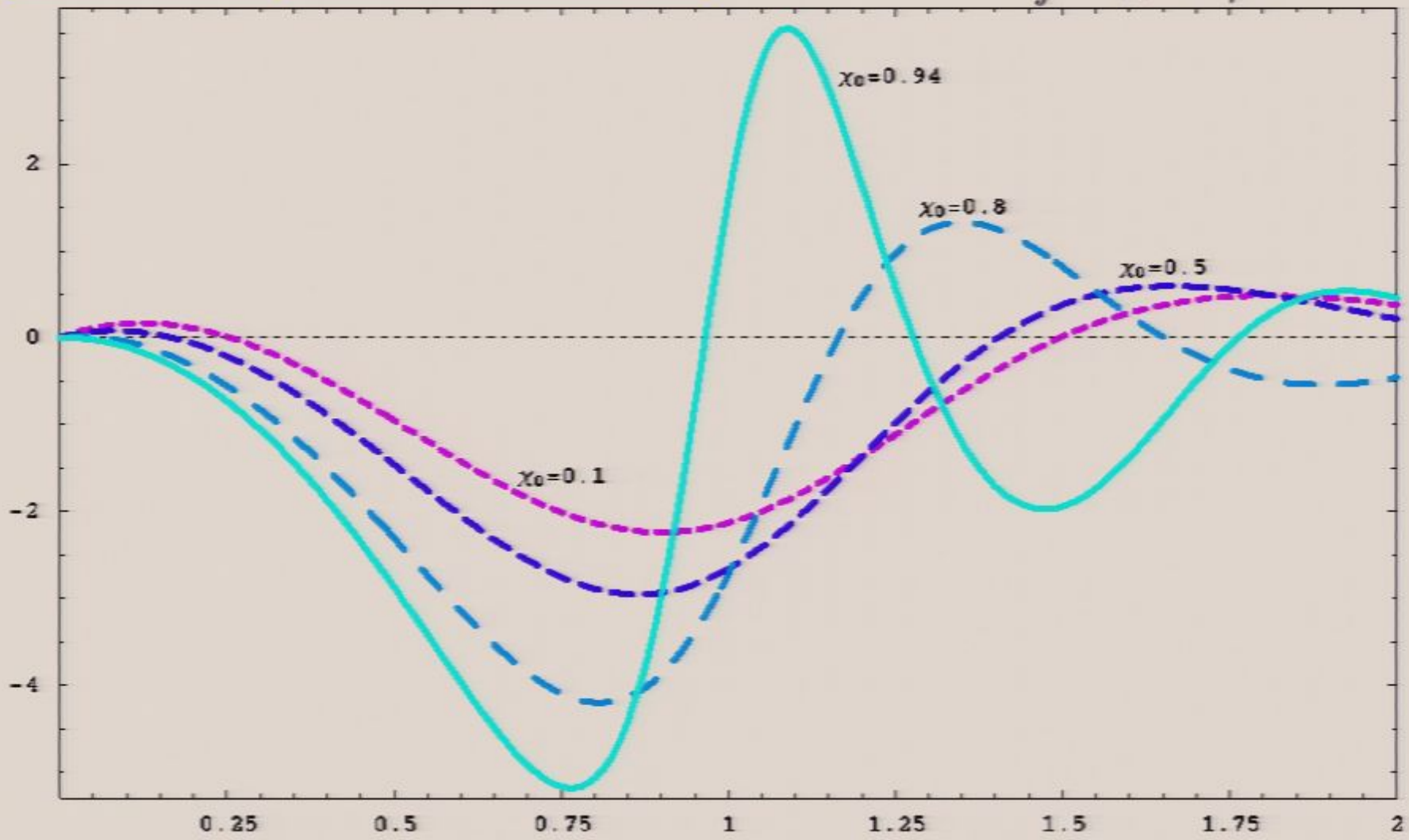
3. Transport properties of plasma
   $\longrightarrow$ diffusivity, viscosity, spectral functions, ...

4. Conclusions/Outlook

Thermal spectral function:

subract off asymptotic tail:

$$N_f\, N_c\, \omega^2/4\pi$$



- approaching phase transition, structure builds

→ quasinormal frequencies approach real axis

Shear viscosity:

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

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

[Son & Starinets; Herzog & Son]

- "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])

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

Diffusion of "light" quarks

- conserved current associated with fundamental matter:

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

diffusion of charge via Fick's law: $J^x = -\mathbf{D}\,\partial_x J^0$

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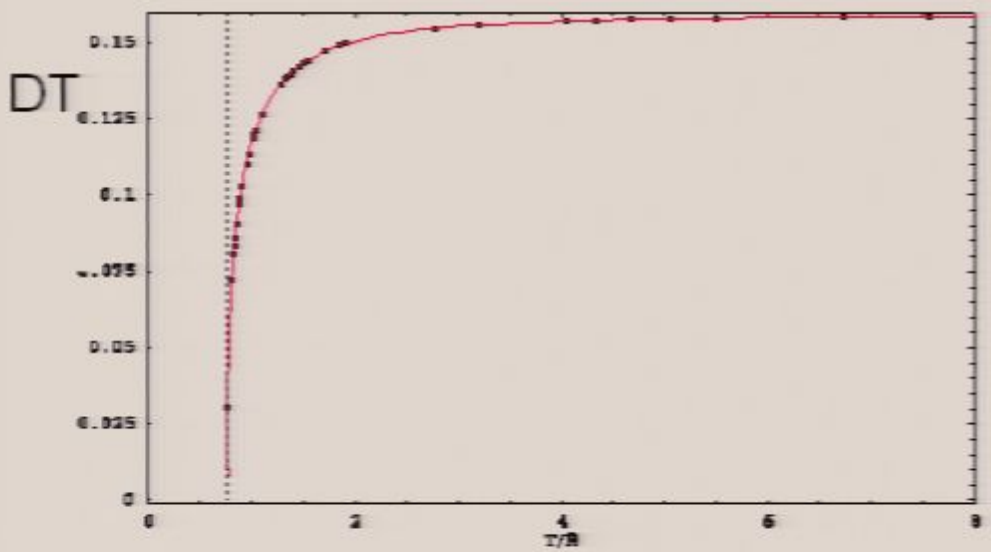
- for black hole embeddings, associated diffusion constant can be calculated from:
  - → spectral density given susceptibility $\partial\rho/\partial\mu|_{\mu=0}$
  - → "sound" mode in charge-charge correlator
  - → membrane paradigm

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

Diffusion of flavor charge (in BH phase)



matches KSS result for R-charge:

$$D = \frac{1}{2\pi T}$$

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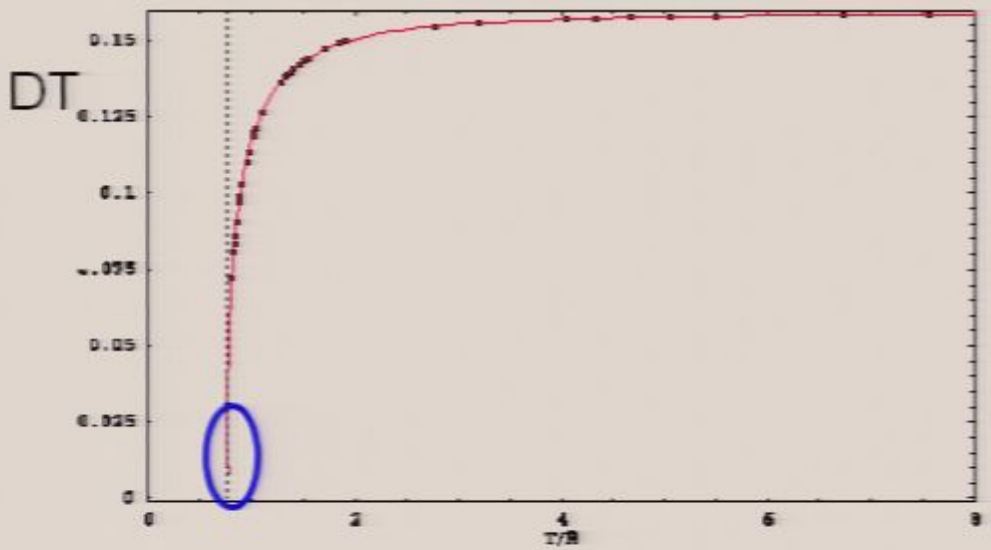

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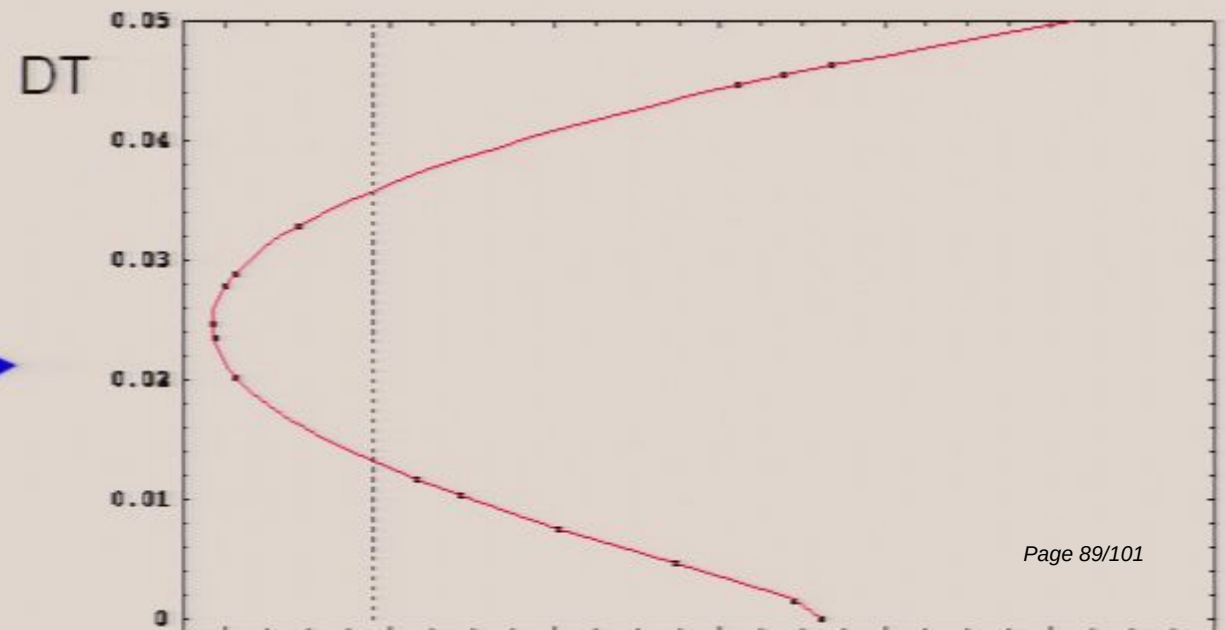

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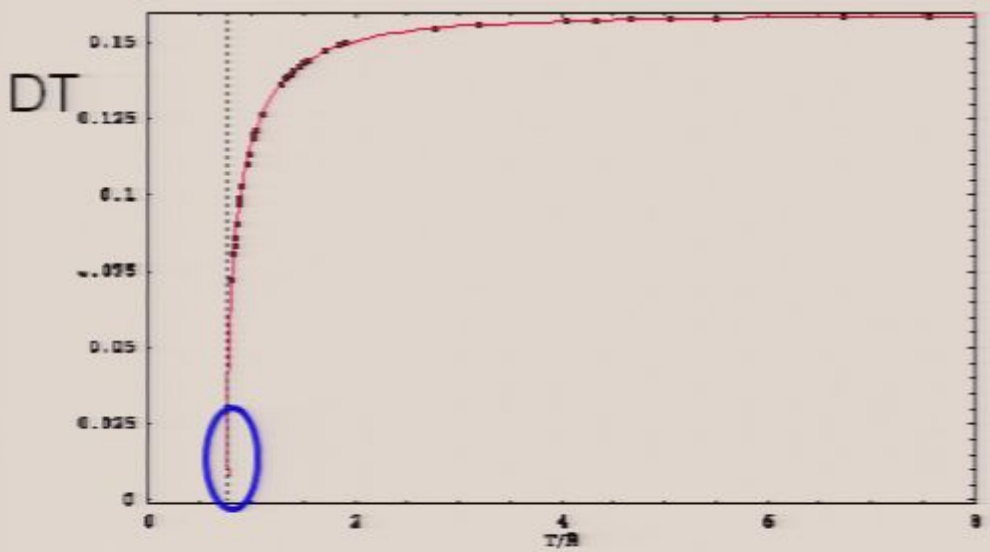

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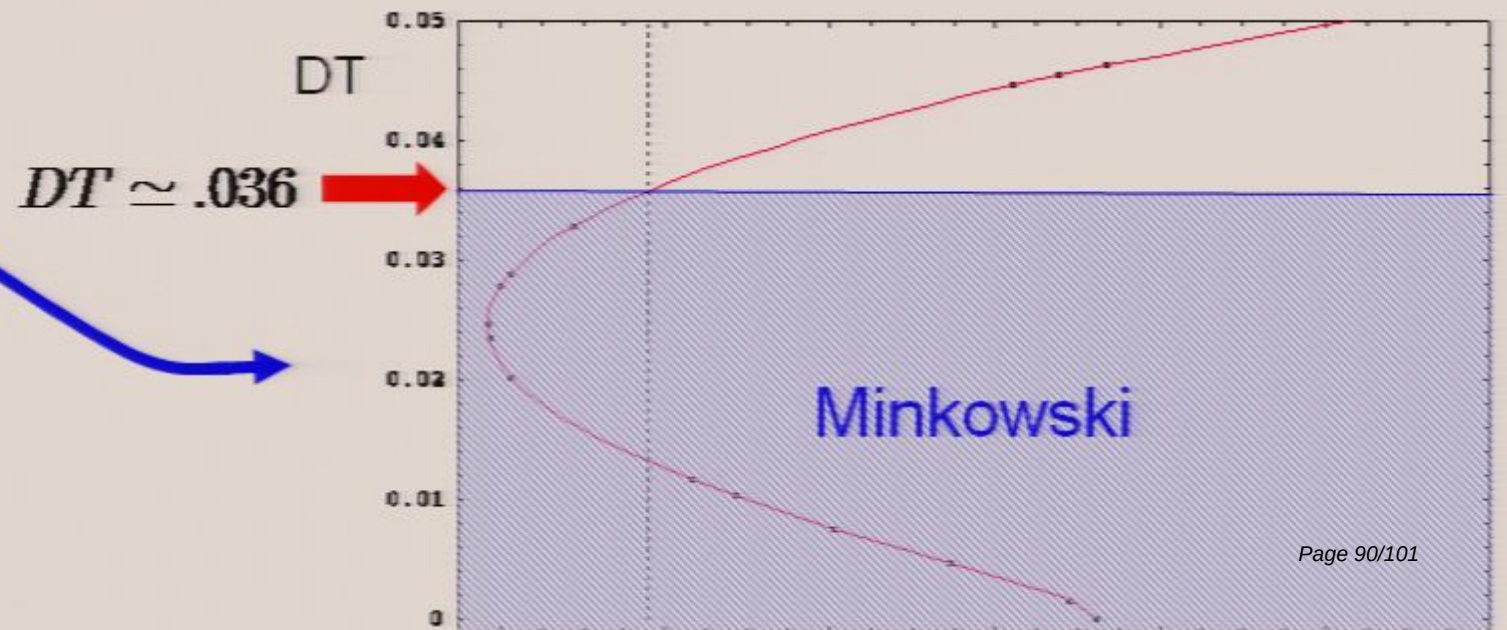
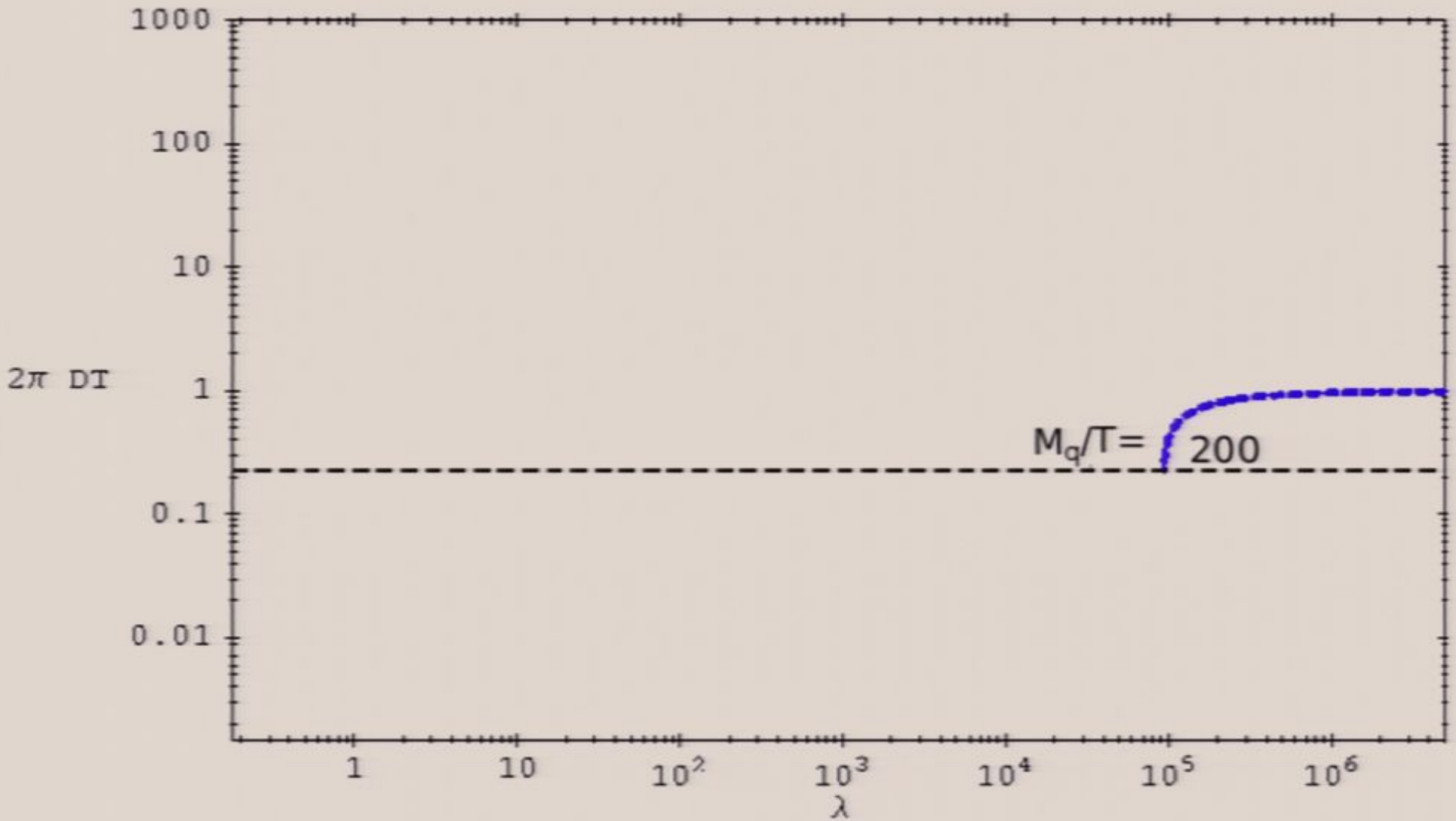


Big Picture:



See also: Liu, Rajagopal & Wiedemann; Gubser. . .

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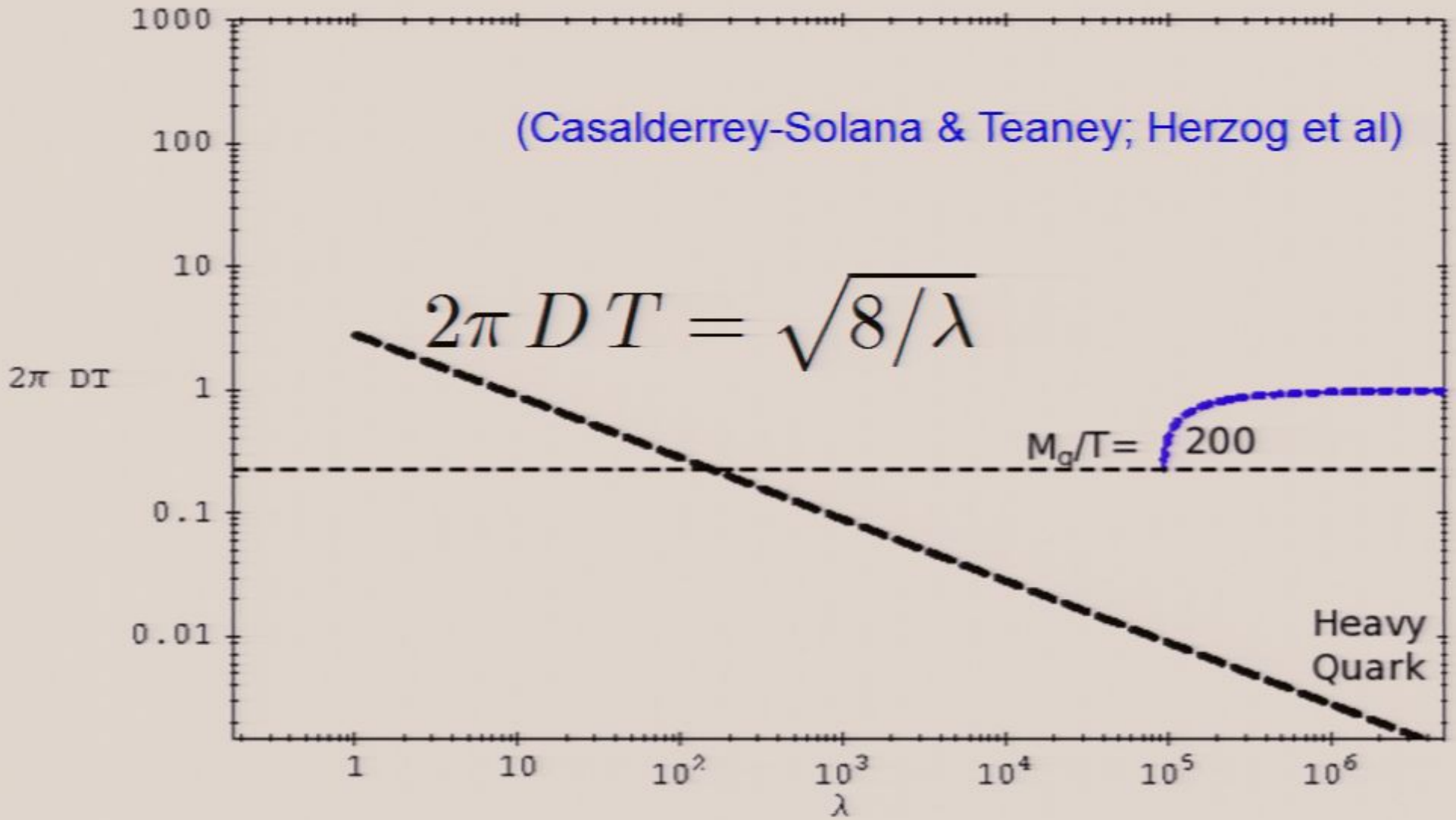

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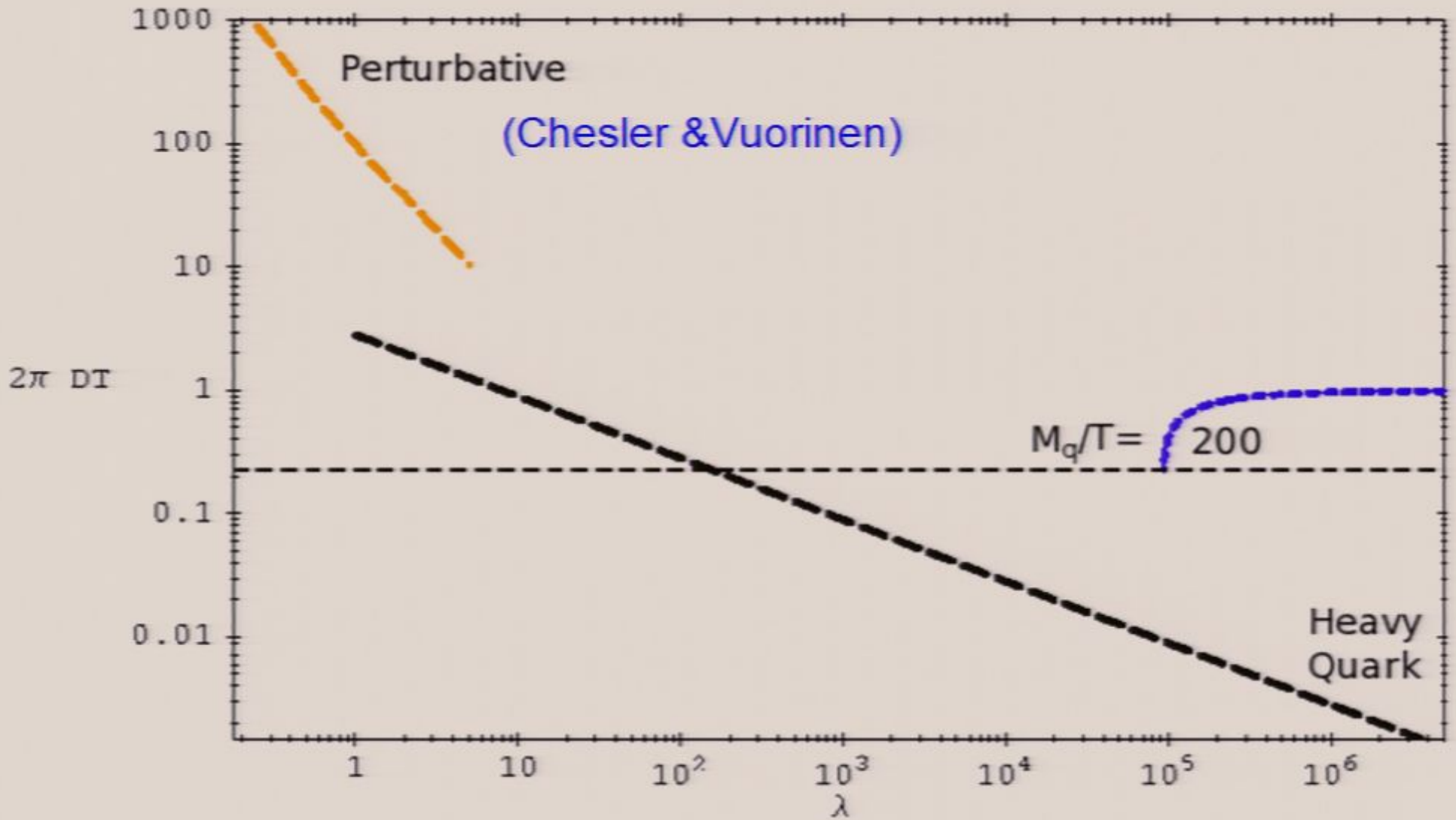
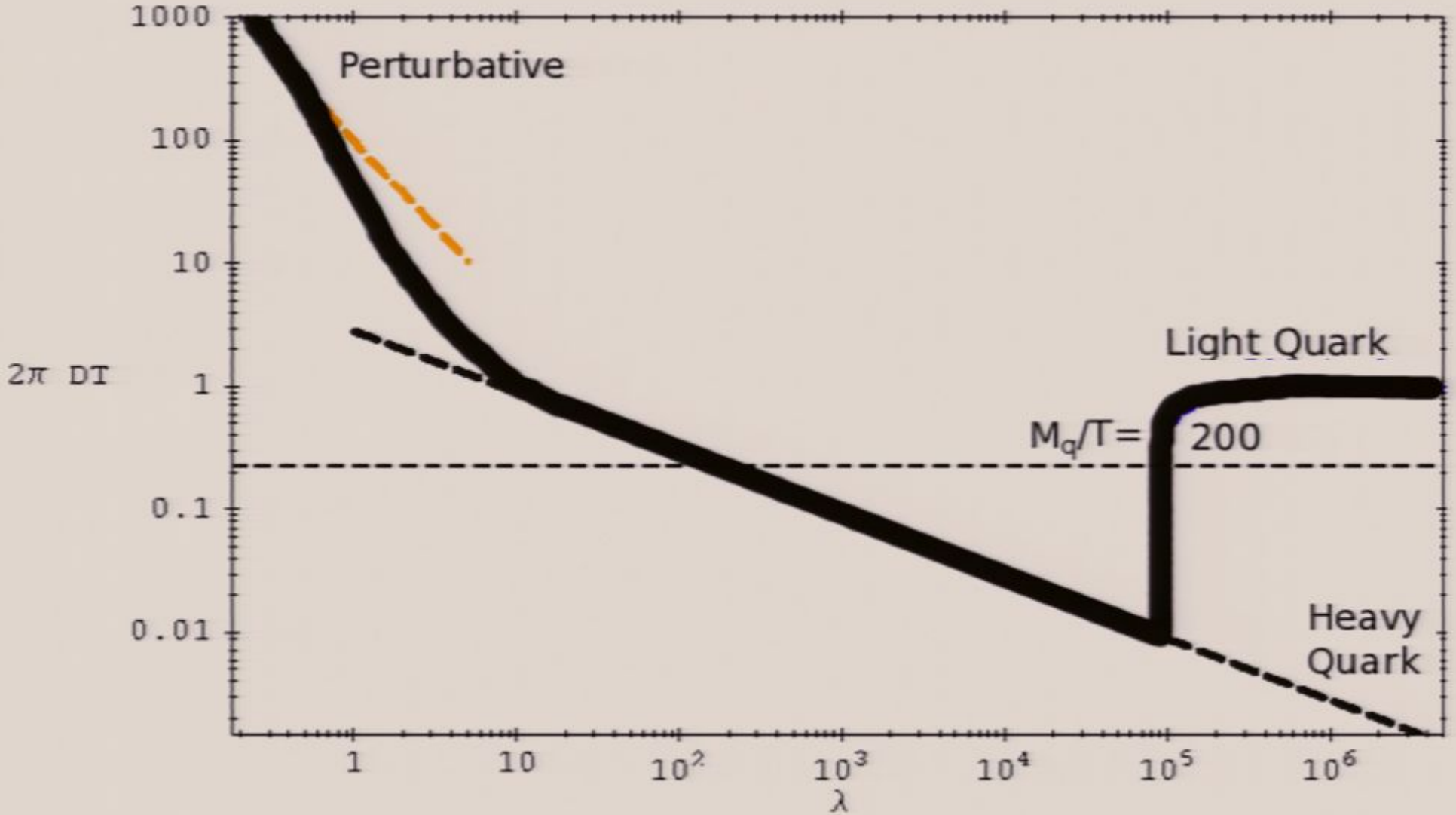

1000
100
10
1
0.1
0.01
2π DT
Perturbative
(Chesler &Vuorinen)
$M_q/T=$ 200
Heavy
Quark
1
10
10^2
10^3
10^4
10^5
10^6
λ

Big Picture:


1000
100
10
1
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2π DT
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Light Quark
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1
10
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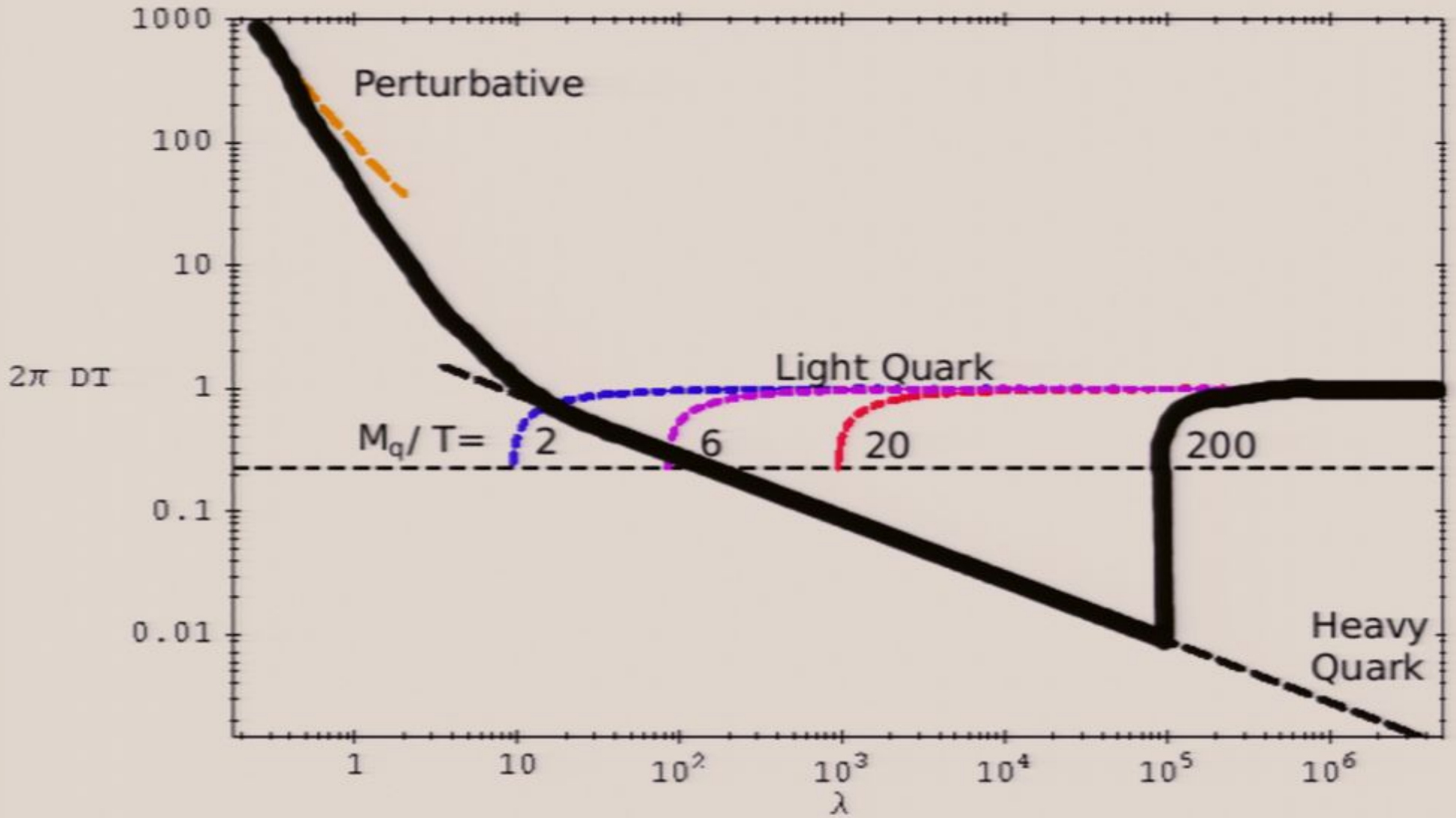
1000
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2π DT
Perturbative
Light Quark
Heavy Quark
M_q/ T=
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6
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200
1
10
10^2
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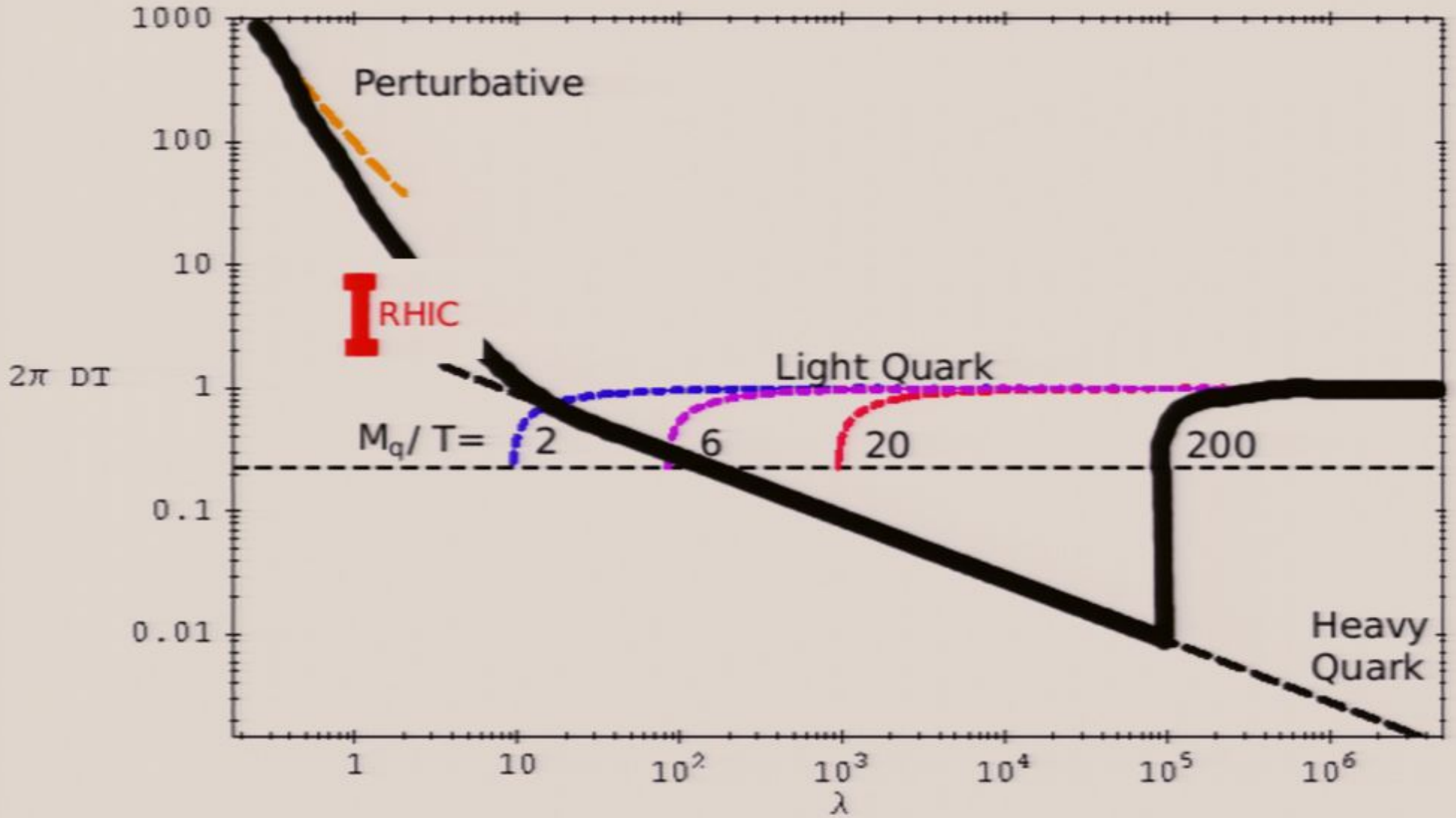
1000
100
10
1
0.1
0.01
2π DT
Perturbative
RHIC
Light Quark
M_q/ T=
2
6
20
200
Heavy Quark
1
10
10^2
10^3
10^4
10^5
10^6
λ

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:

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

⟶ thermal spectral functions

- adding chemical potential/finite baryon density

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Three more talks to come – Stay tuned!

Shear viscosity:

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

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

[Son & Starinets; Herzog & Son]

- "diffusion constant" for conserved stress-energy

[Policastro, Son & Starinets]

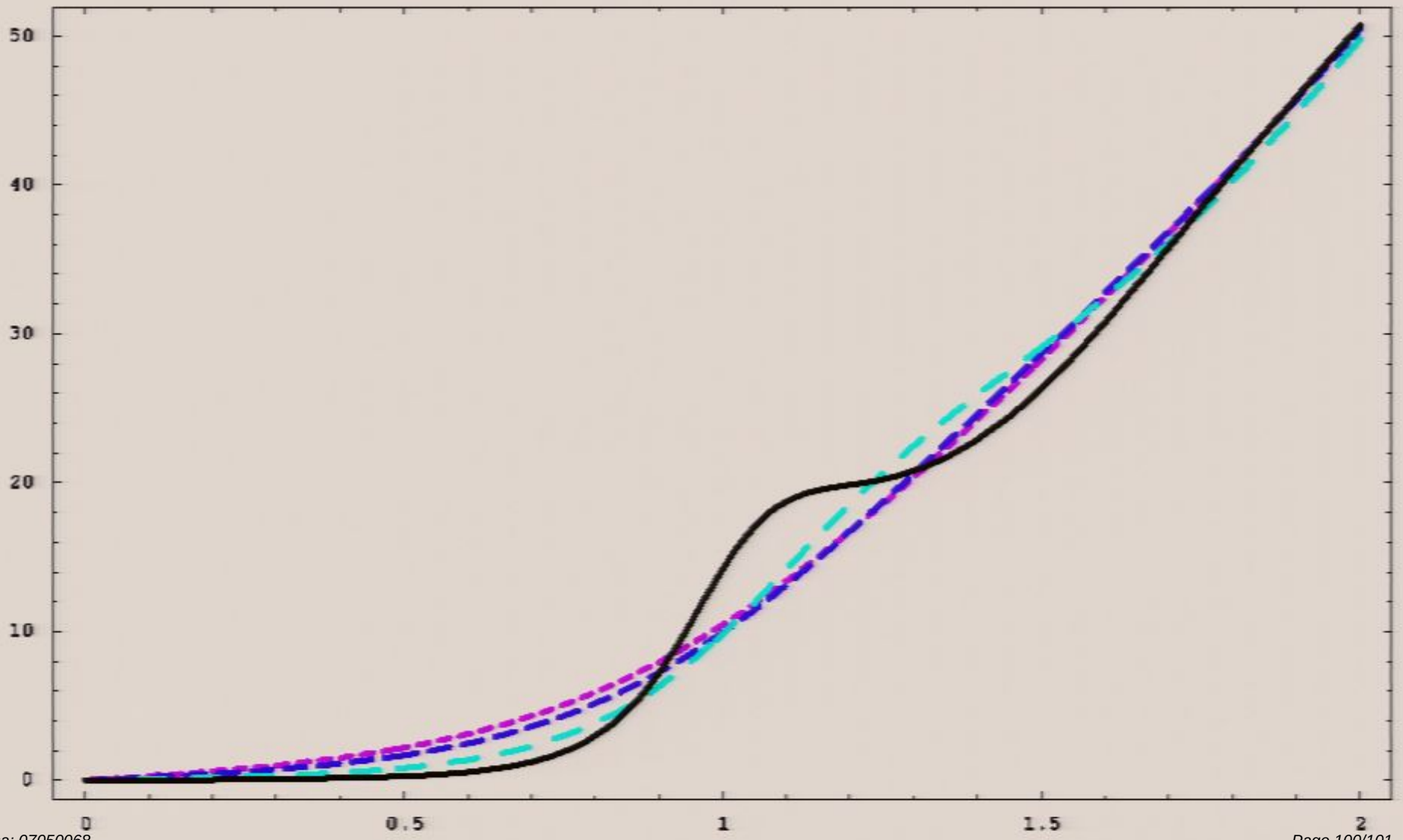
- gravity result: $\eta = \frac{\pi}{8} N_c^2 T^3$
- "small" – compare perturbative results: $\eta \sim \frac{N_c^2 T^3}{\lambda^2 \log(1/\lambda)}$
  – compare RHIC results
- universal result for all known theories with gravity dual:

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

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

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

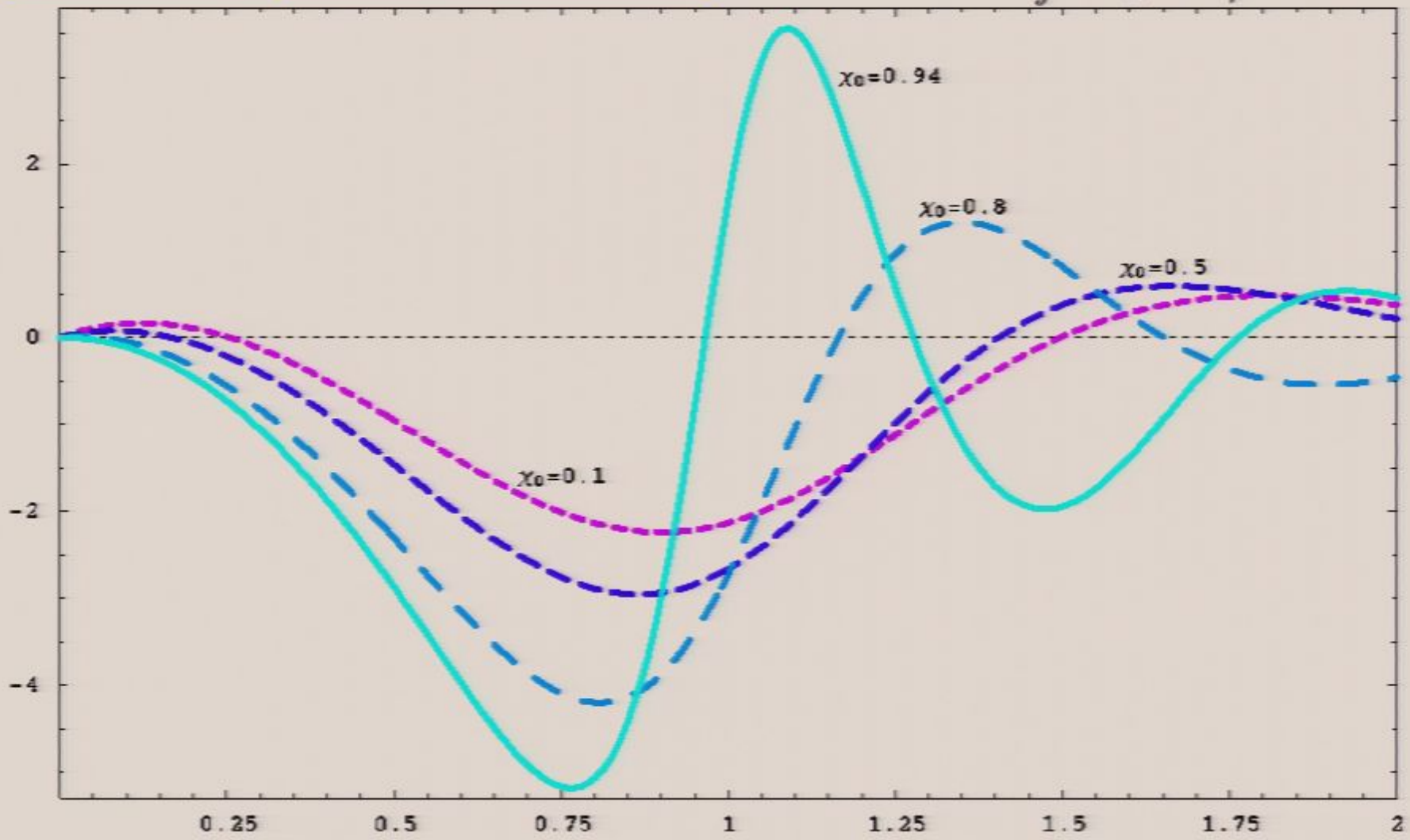
Thermal spectral function: pseudoscalar



Thermal spectral function:

subract off asymptotic tail:

$$N_f\, N_c\, \omega^2/4\pi$$



- approaching phase transition, structure builds

→ quasinormal frequencies approach real axis