

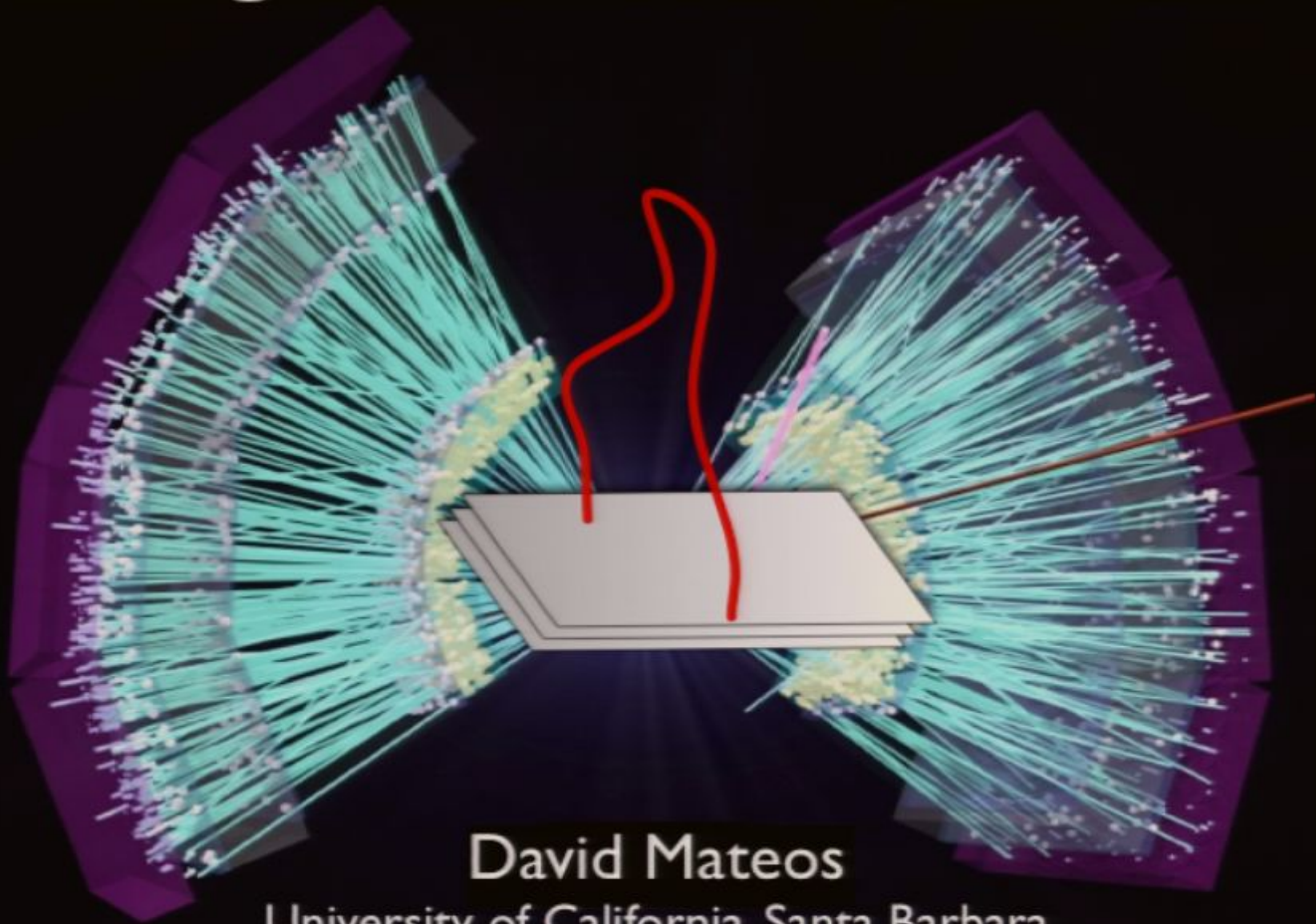
Title: Bright Branes for RHIC

Date: May 24, 2007 02:40 PM

URL: <http://pirsa.org/07050069>

Abstract:

# Bright Branes for RHIC



David Mateos

University of California, Santa Barbara

# Plan

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i) Motivational remarks.

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- ii) Photon production.



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Comments/corrections welcome!

iii) Viscosity of fundamental matter.

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v) Future directions.

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# The QCD challenge



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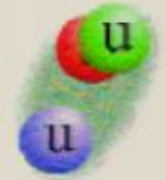
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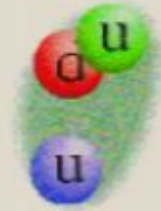
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- Lots of gauge/gravity examples.



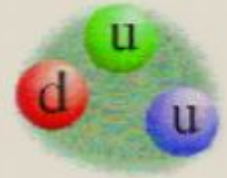
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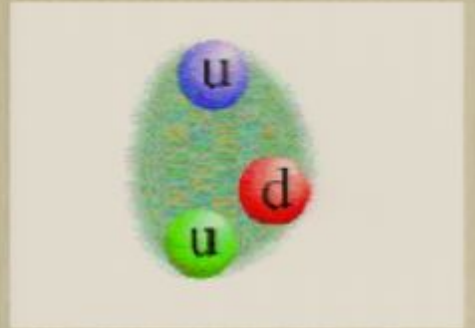
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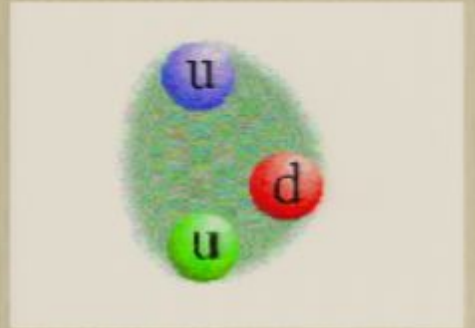
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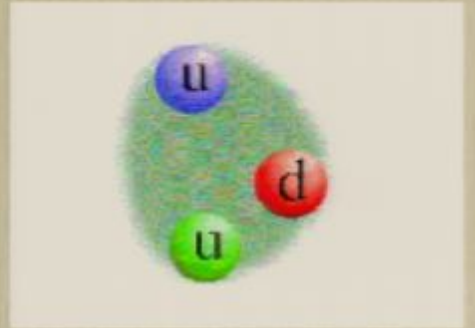
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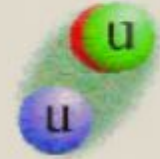


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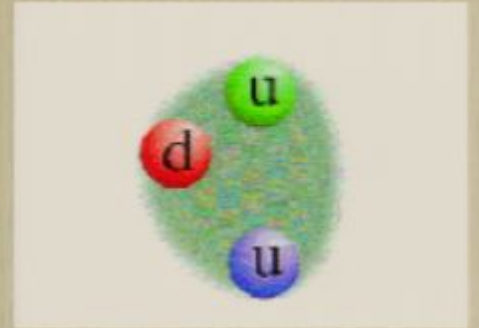
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- However, certain predictions may be universal enough to apply in certain regimes.
- Good example:  $\eta/s = 1/4\pi$  Pollicastro, Son & Starinets '01
- Same for all gauge theories with gravity dual:  
Different dimensions, with or without fundamental matter, with or without chemical potential, etc.



# Observations:

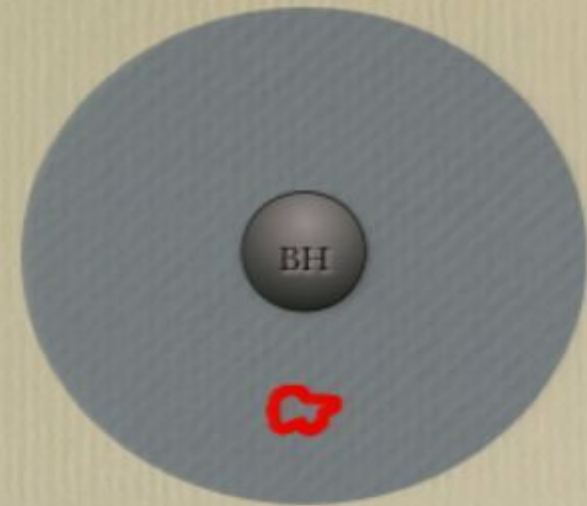


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- But PSS did not know this!

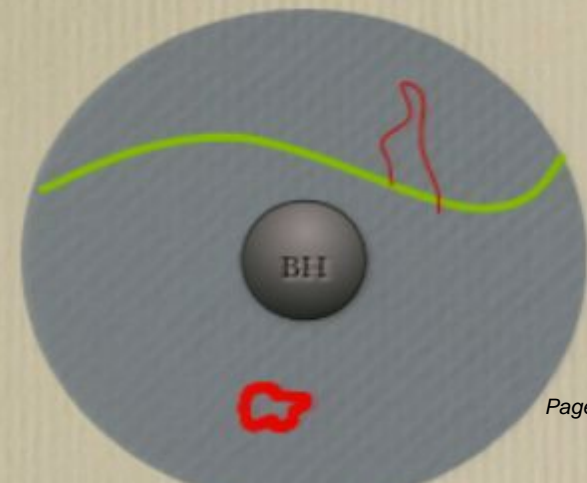
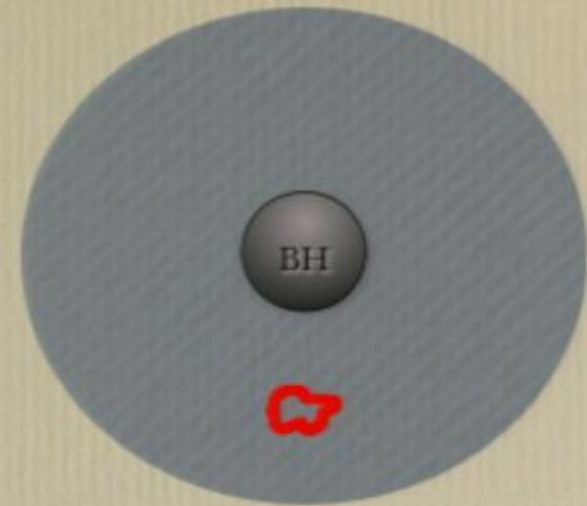
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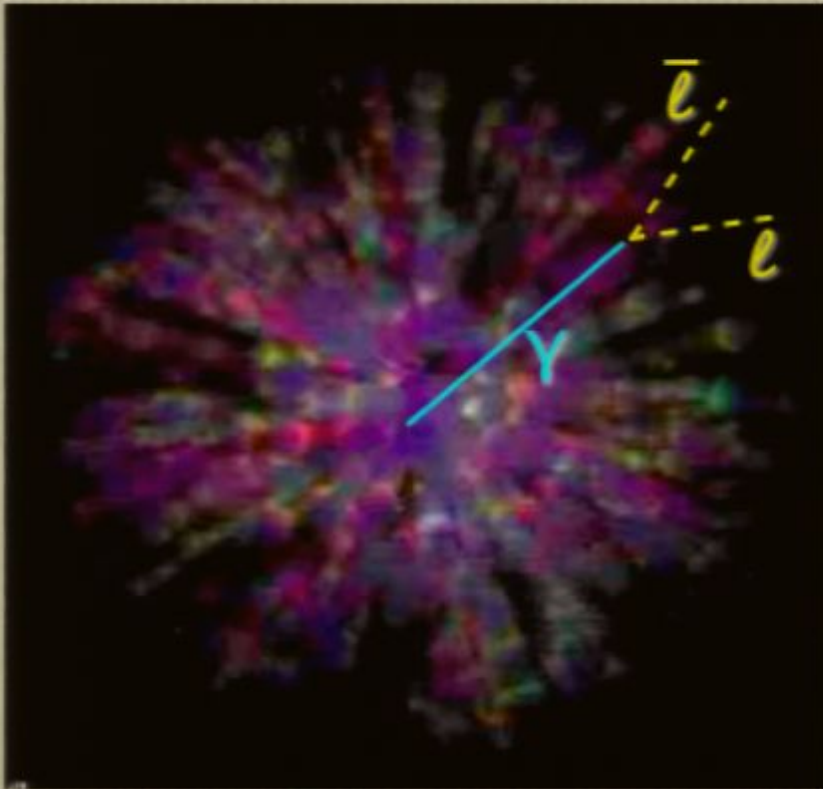
- But PSS did not know this!
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- Combine with another one:  
 $N_f \ll N_c$  quark flavours correspond to  $N_f$  probe branes



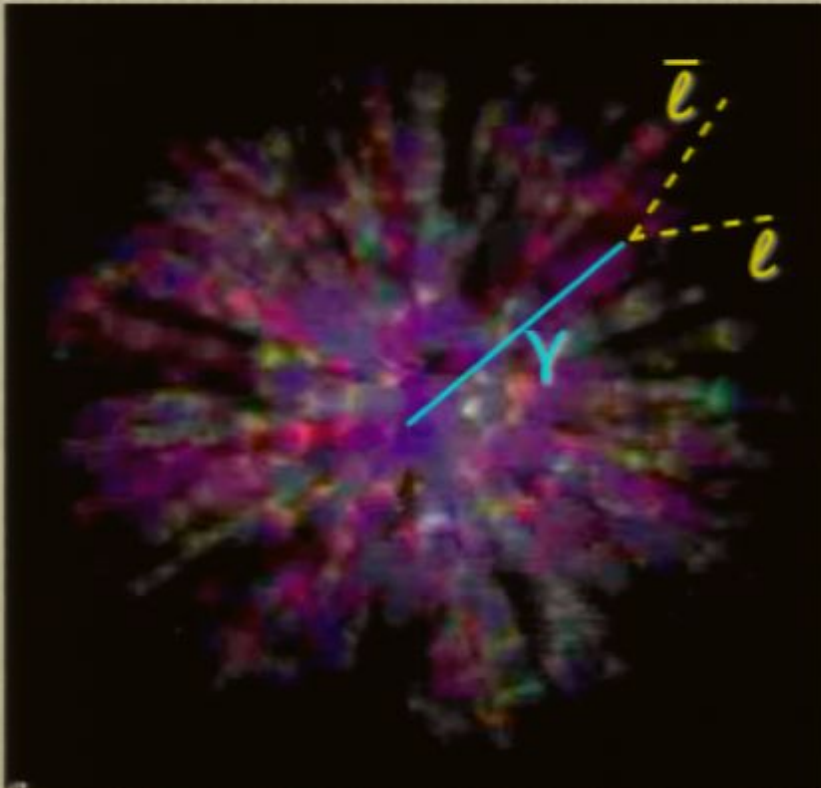
## ii) Photon production.

D.M., Patiño-Jaidar



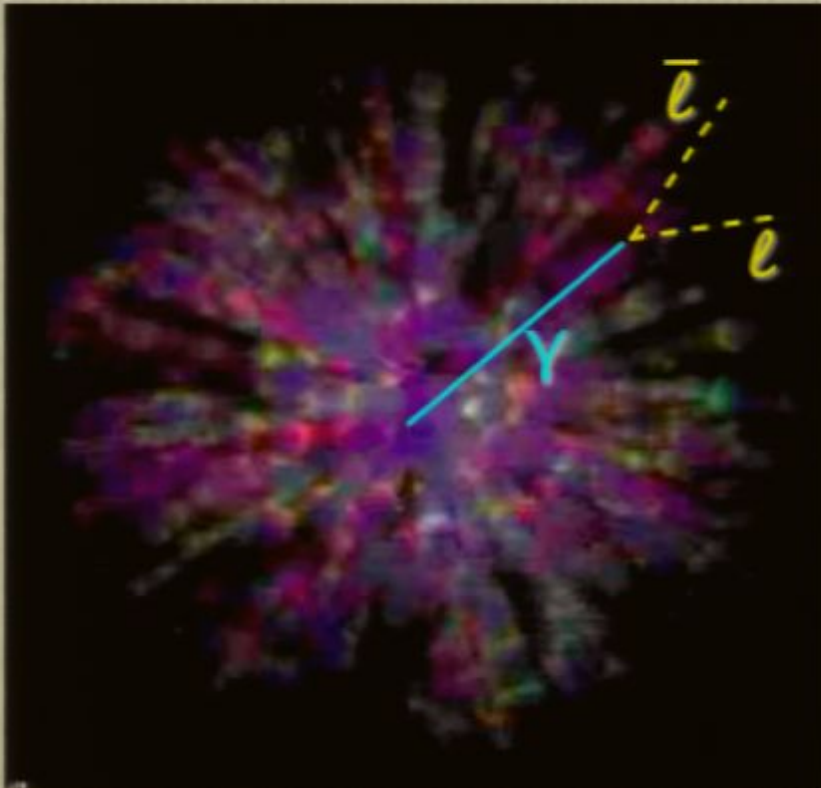


- QGP is optically thin  $\rightarrow$  Photons carry valuable information.



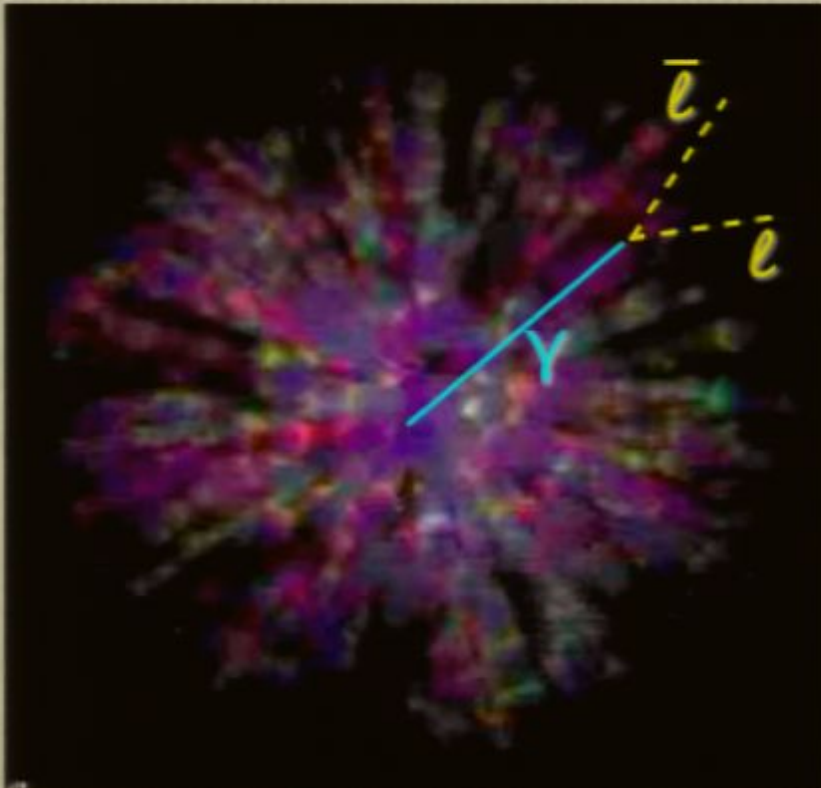
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- To couple to electromagnetism we gauge the  $U(1)_B$ :

$$\mathcal{L} = \mathcal{L}_{SU(N_c)} - \frac{1}{4} \mathcal{F}_{\mu\nu}^2 + e \mathcal{A}^\mu J_\mu^{\text{EM}}$$

$$J_\mu^{\text{EM}} = \bar{\Psi} \gamma_\mu \Psi + \frac{i}{2} \Phi^* \mathcal{D}_\mu \Phi - \frac{i}{2} (\mathcal{D}_\mu \Phi)^* \Phi$$

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- Note: We assign zero electric charge to adjoint matter.



- In this way we obtain an  $SU(N_c) \times U(1)_{\text{EM}}$  theory in which, to leading order in “e”:

$$\frac{d\Gamma}{d^d\mathbf{k}} = \frac{e^2}{(2\pi)^d 2|\mathbf{k}|} \frac{1}{e^{k^0/T} - 1} \eta^{\mu\nu} \chi_{\mu\nu}(k)$$

$k = (k^0, \mathbf{k})$ , with  $k^0 = |\mathbf{k}|$ , is the photon null momentum

$\chi_{\mu\nu}(k) = -2 \text{Im } G_{\mu\nu}^{\text{R}}(k)$  is the spectral density

$$G_{\mu\nu}^{\text{R}}(k) = -i \int d^{d+1}x e^{-ik \cdot x} \Theta(x^0) \langle [J_{\mu}^{\text{EM}}(x), J_{\nu}^{\text{EM}}(0)] \rangle$$

- Thus we need correlator in  $SU(N_c) \times U(1)_{\text{EM}}$  theory:

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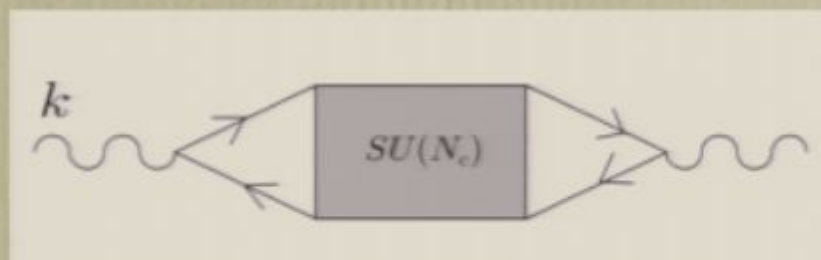
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- However, to leading order in “e” we can:

(I) Drop  $\mathcal{A}_{\mu}$  in the current.

(I) Compute correlator in  $SU(N_c)$  theory:





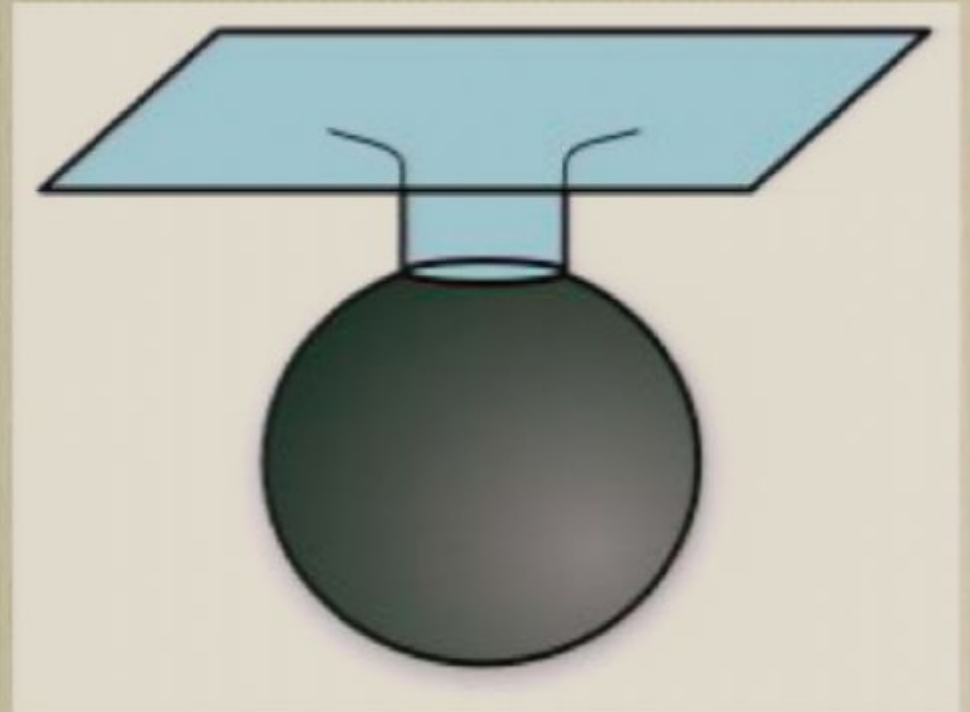
# Holographic calculation

Gauge theory

$N_f$  flavours of equal mass

String theory

$N_f$  overlapping Dq-branes



# Holographic calculation

## Gauge theory

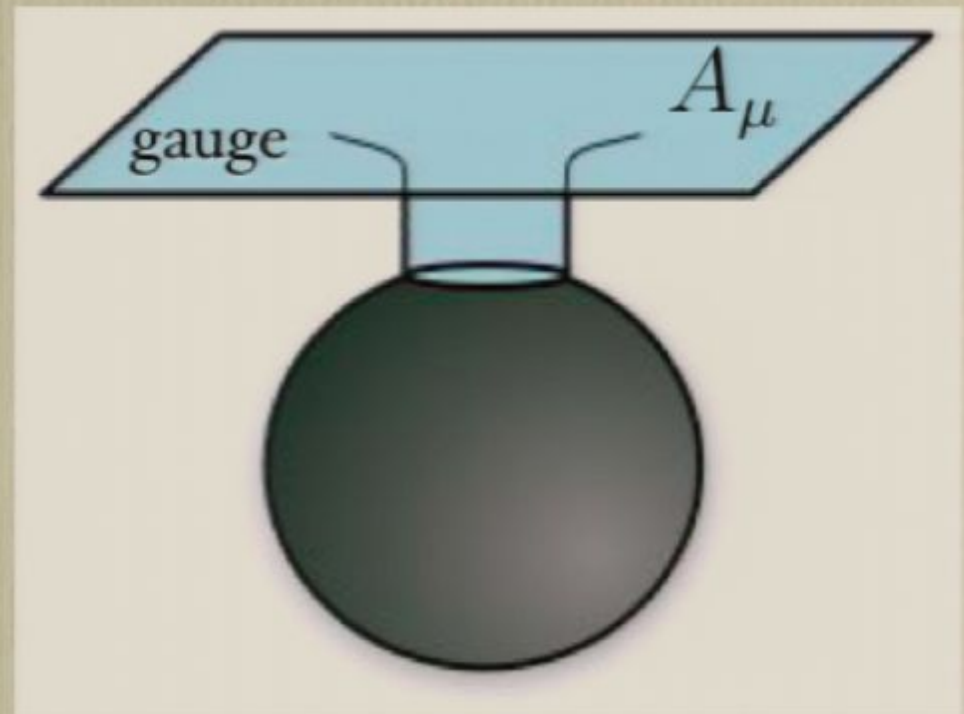
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$$U(N_f) \simeq SU(N_f) \times U(1)_B$$

Conserved  $J_\mu^{\text{EM}}$

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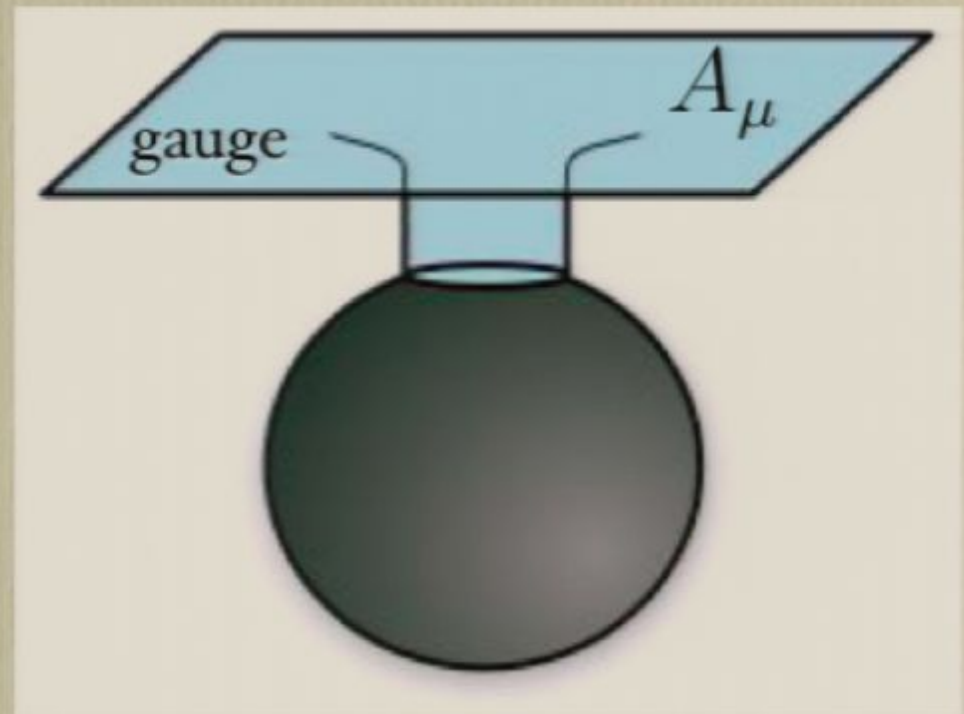
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AdS/CFT prescription:

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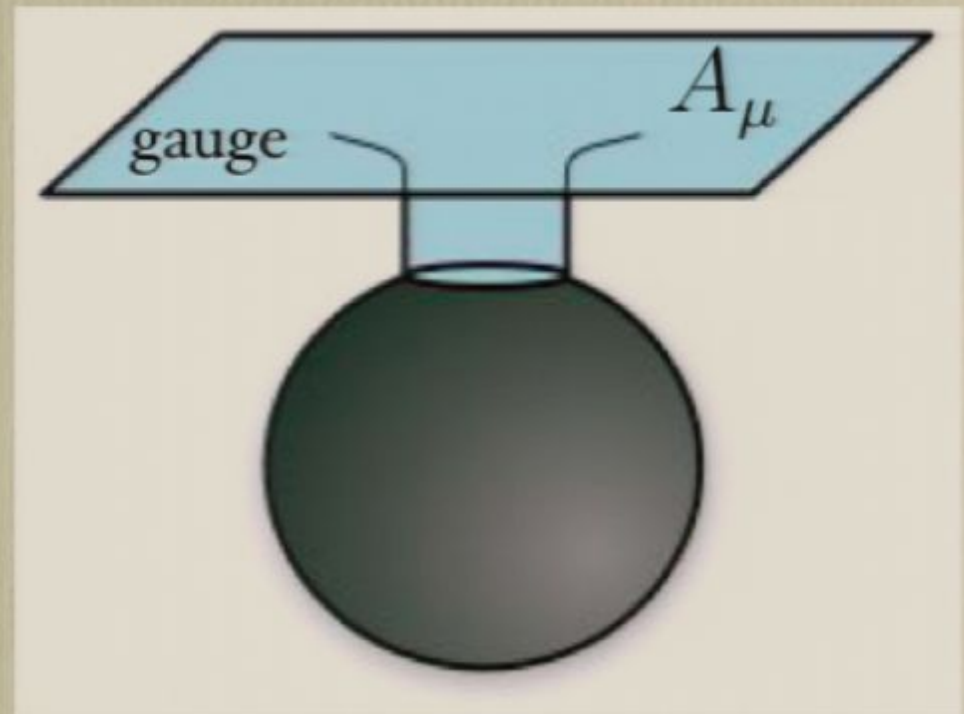
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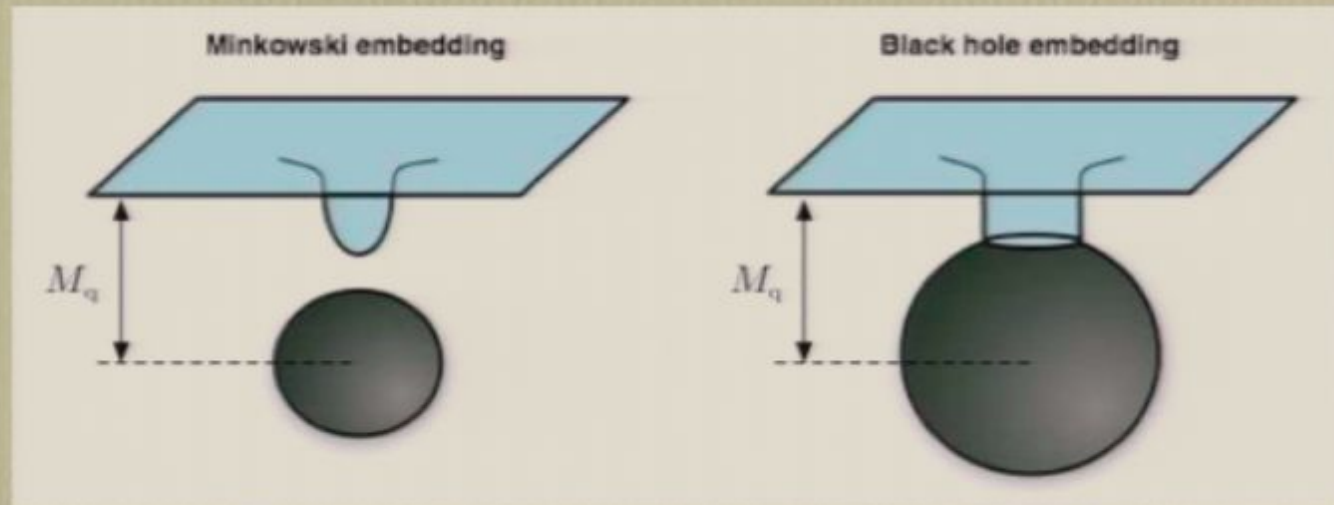
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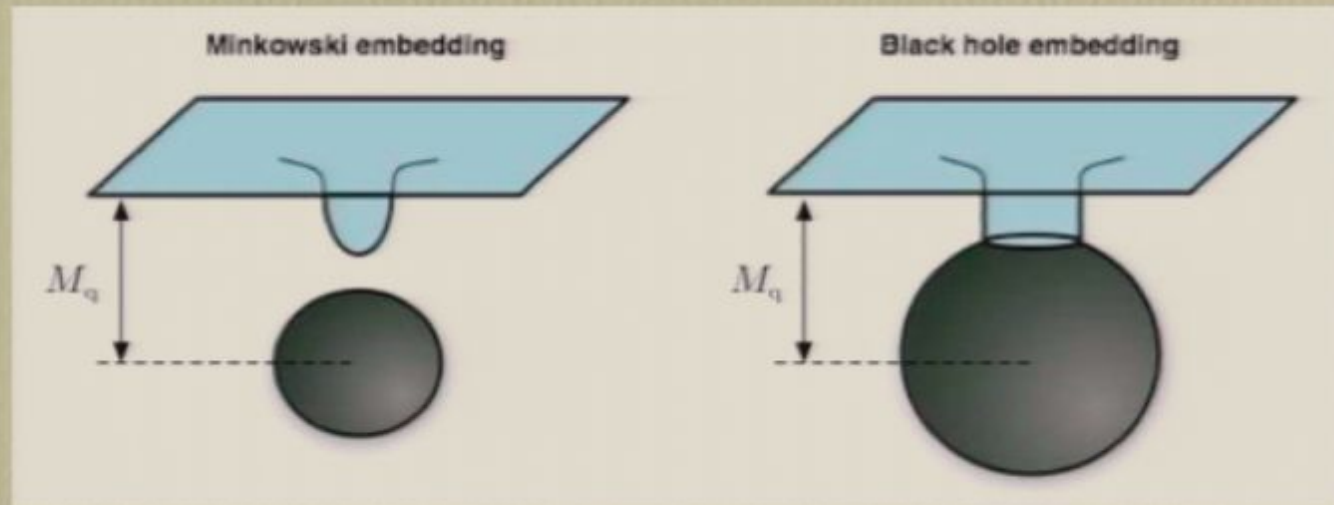
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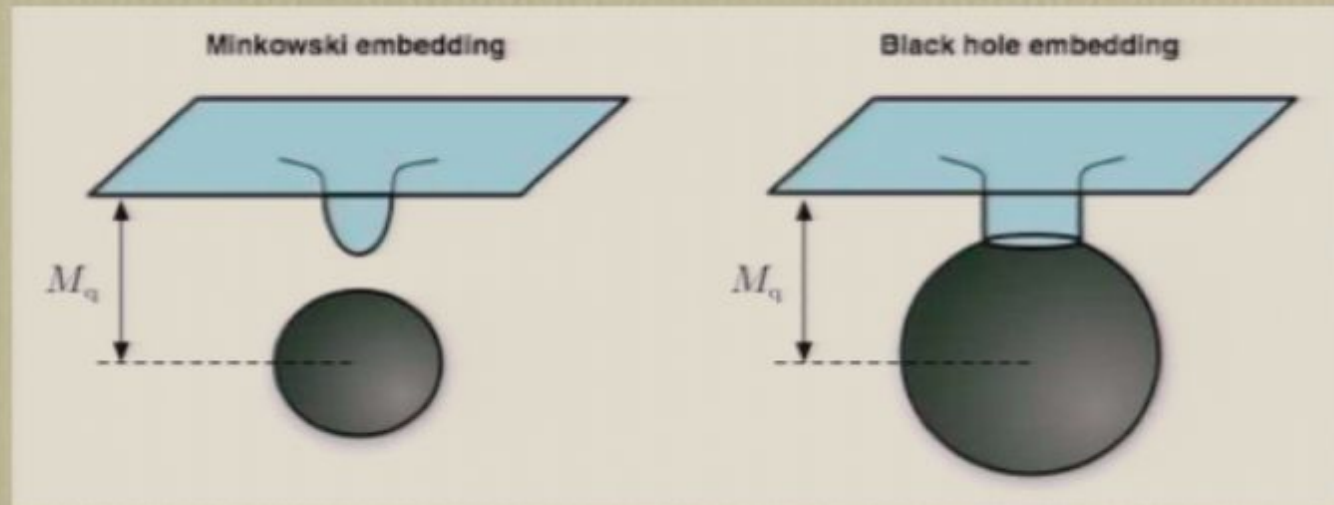
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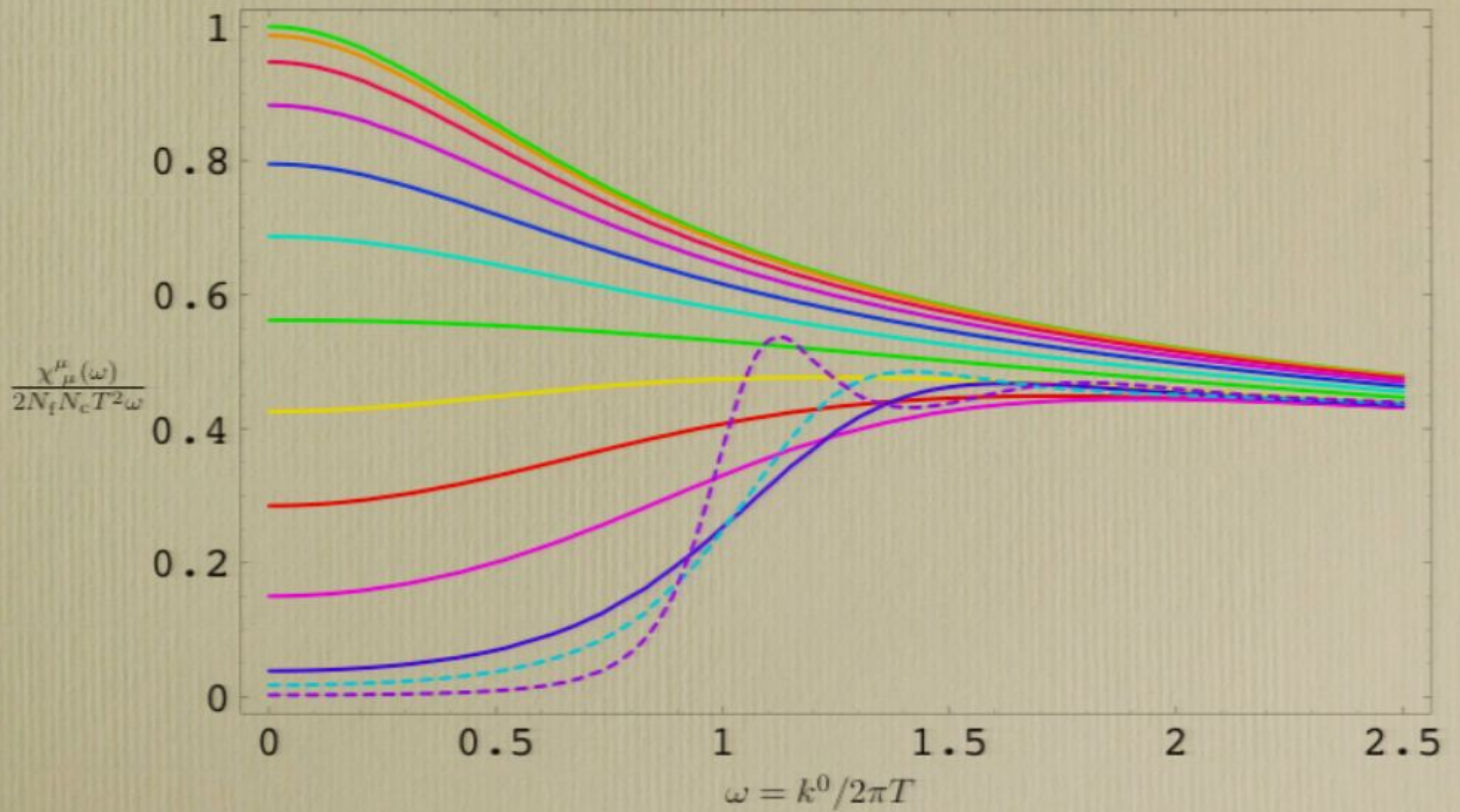
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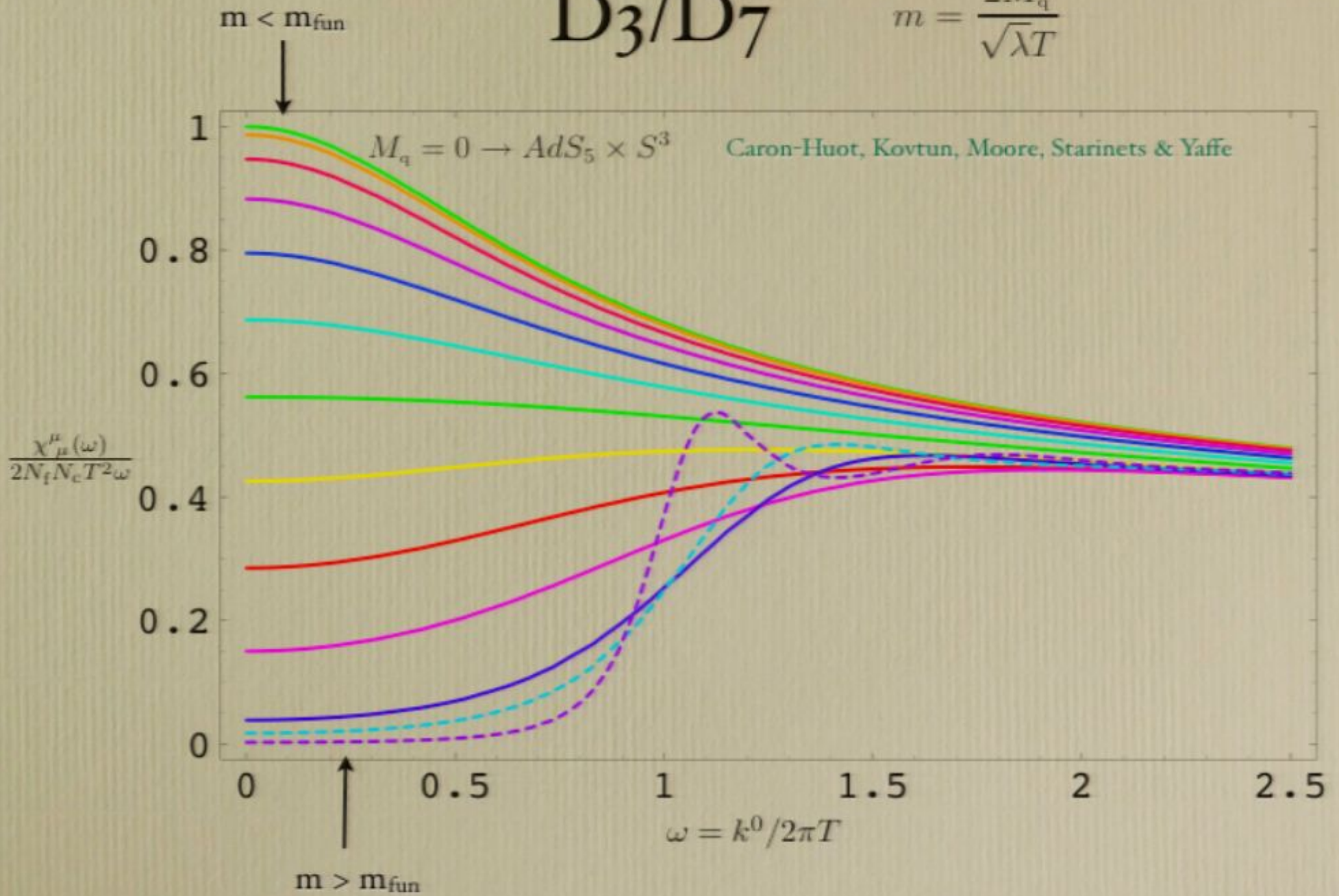
But this assumes existence of quasi-particles!

# D<sub>3</sub>/D<sub>7</sub>



# D3/D7

$$m = \frac{2M_q}{\sqrt{\lambda}T}$$





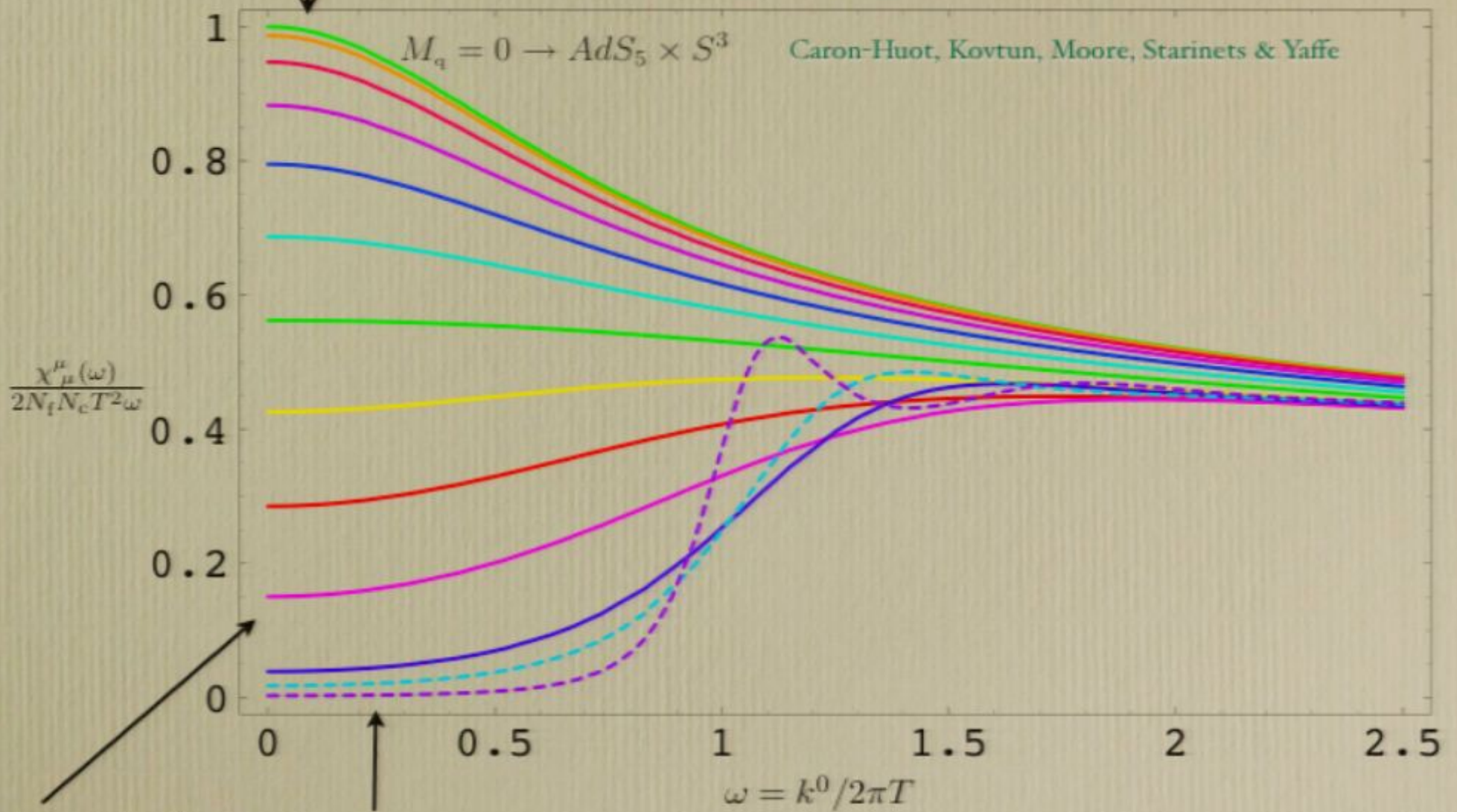
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Area of induced  
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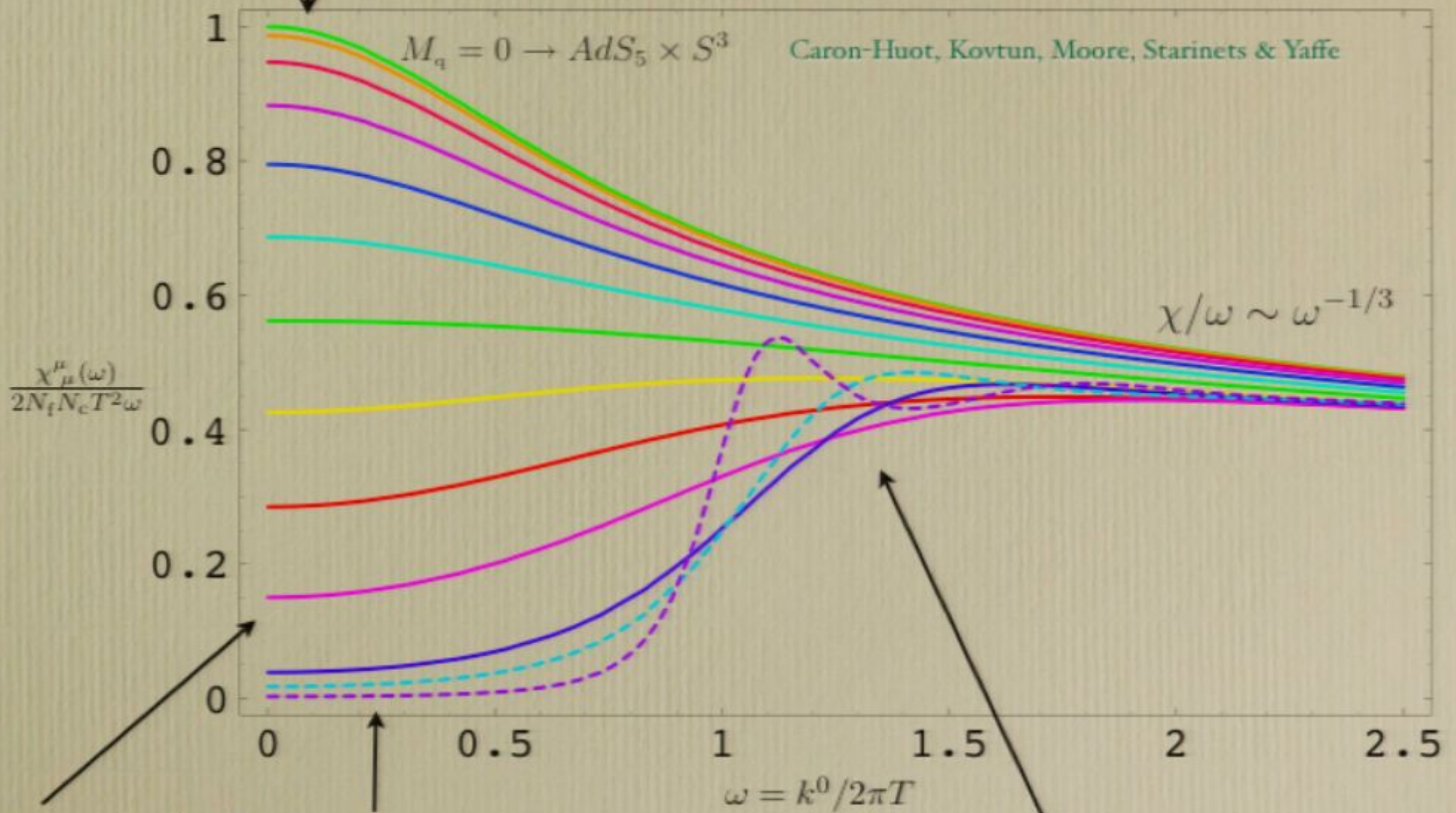
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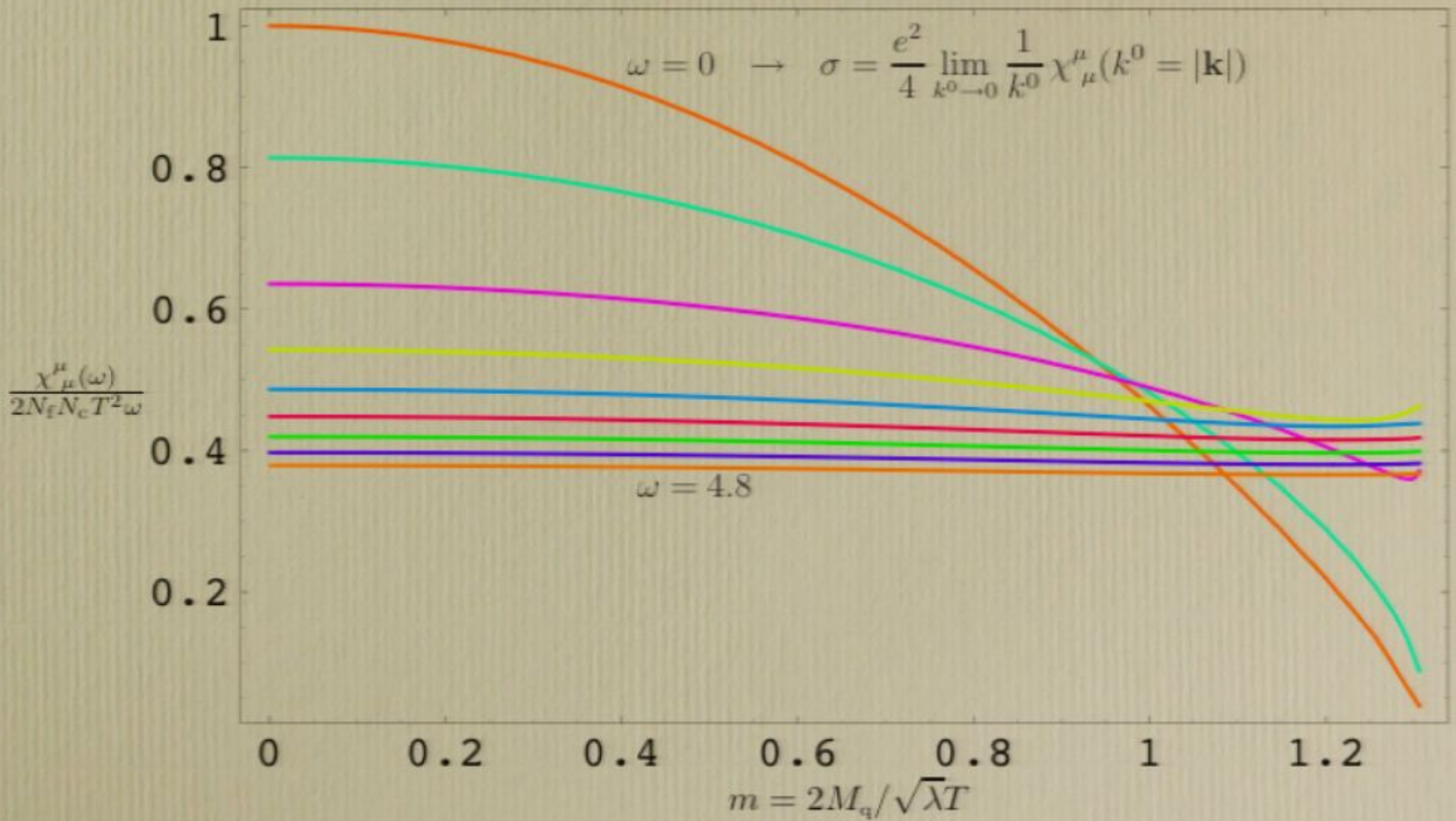
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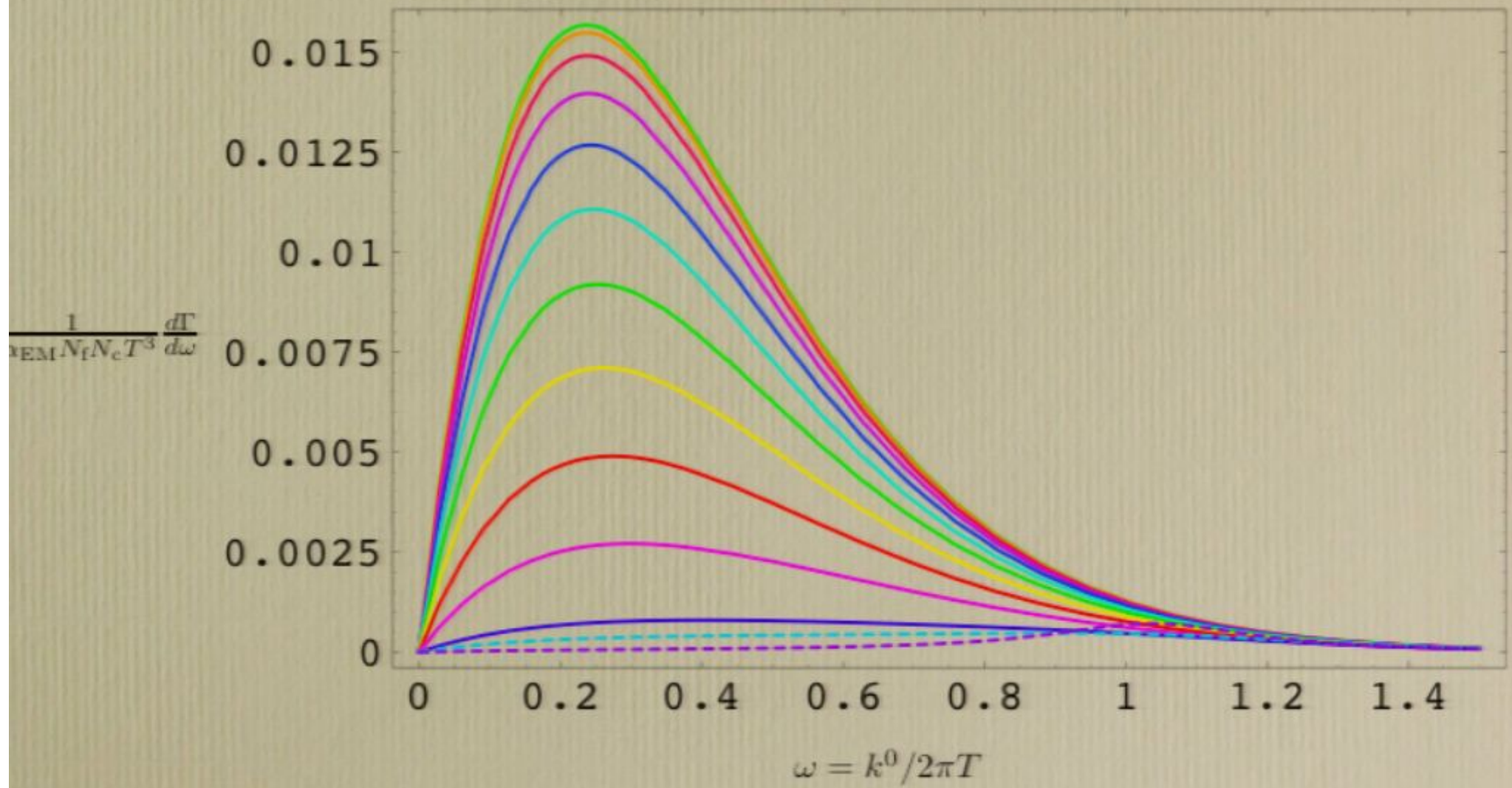


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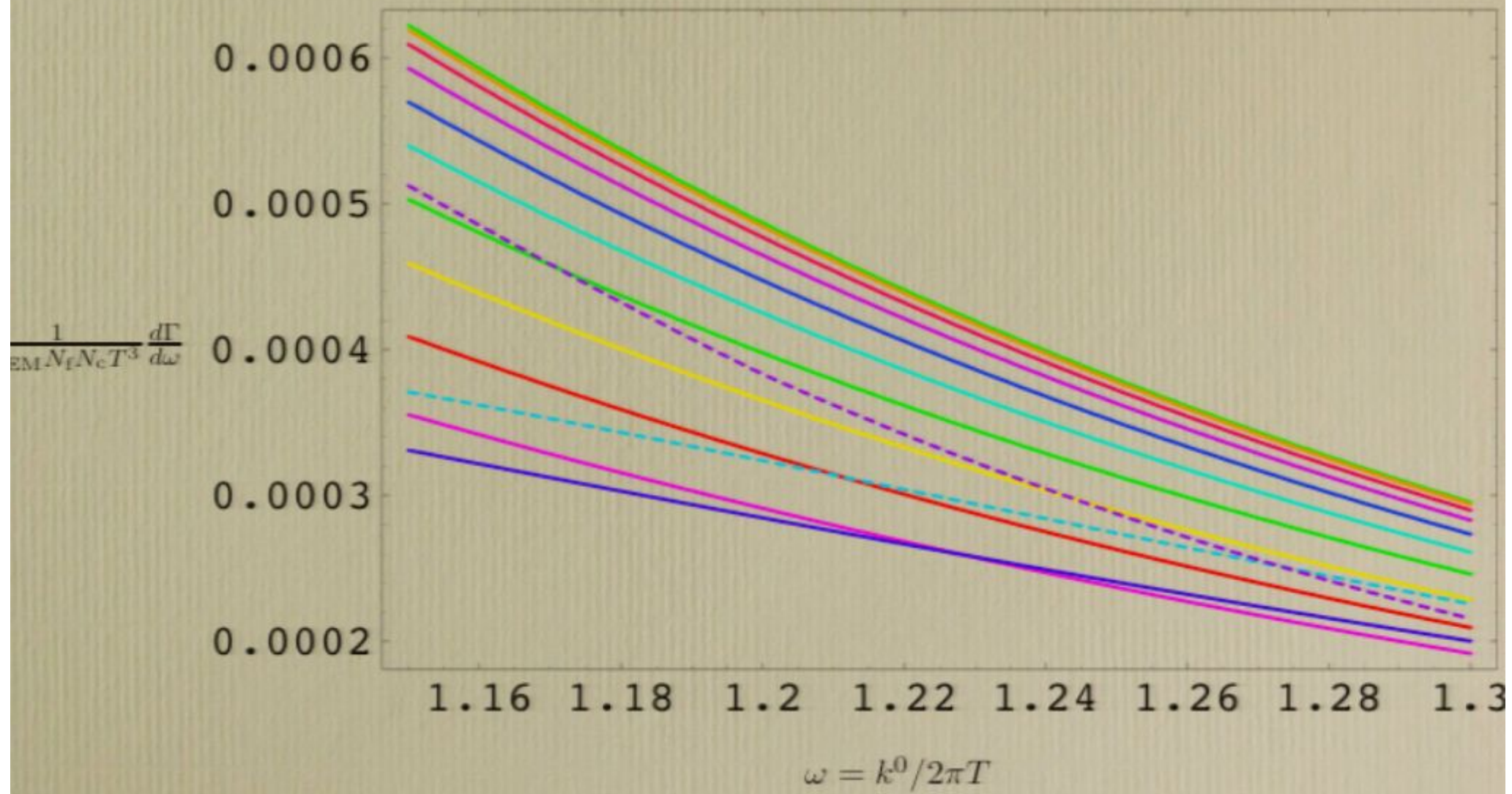




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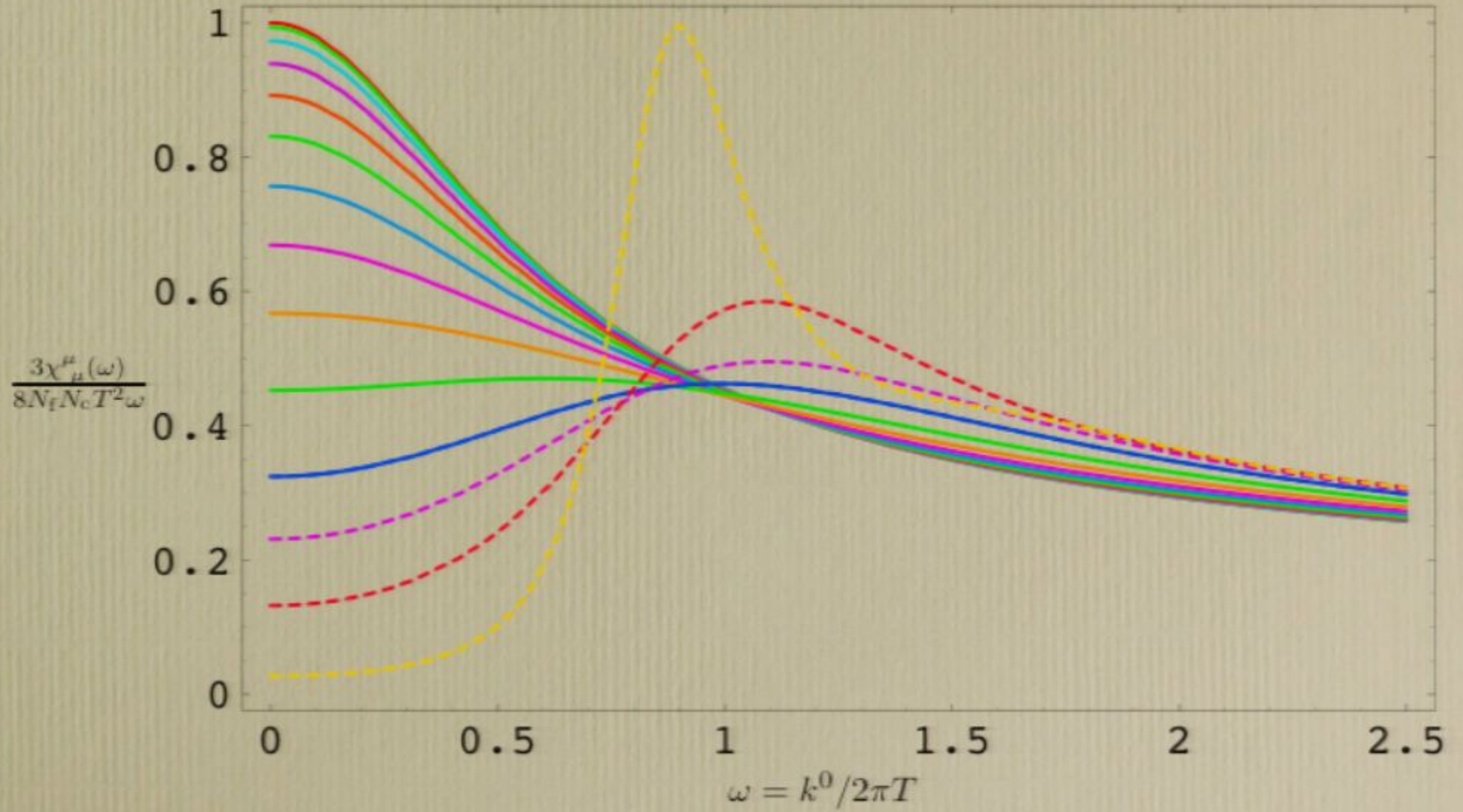


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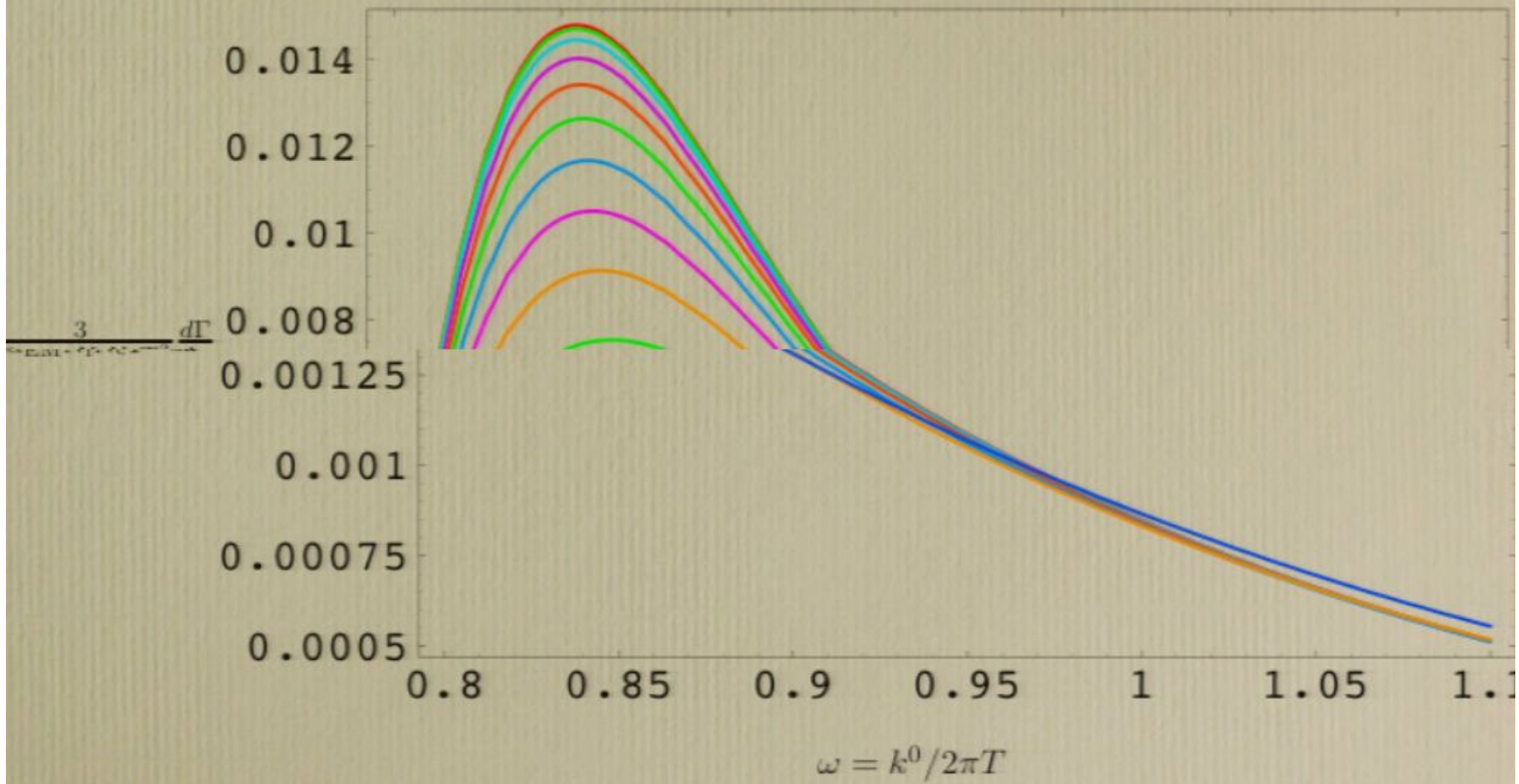


# D<sub>4</sub>/D<sub>6</sub>

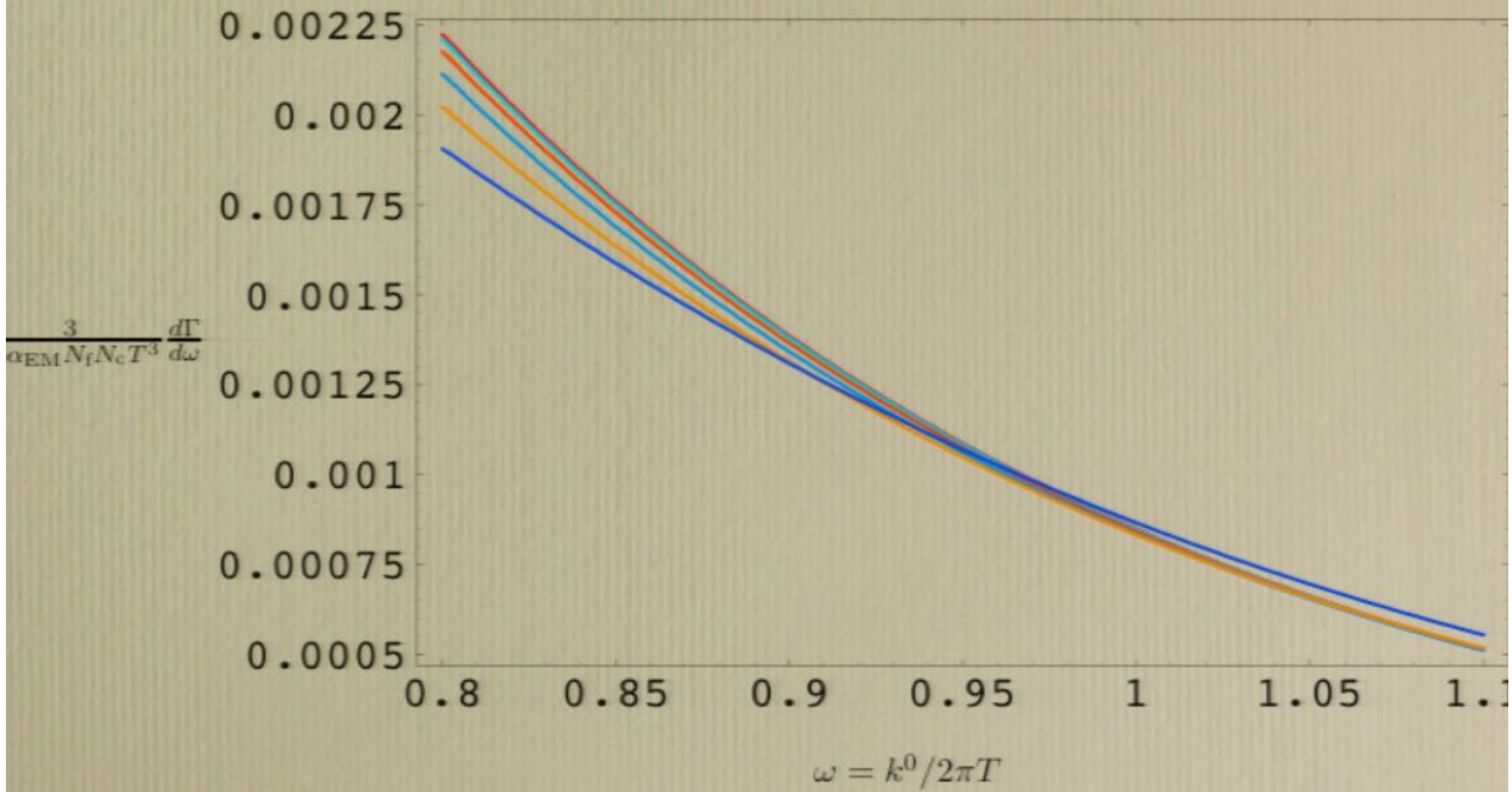




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### iii) Viscosity of fundamental matter.

D.M., Myers & Thomson



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- What about when quarks are included?
- Not only QCD has them, but they provide the leading  $N_f/N_c$  correction.

# Idea


Kubo: 
$$\eta = \lim_{\omega \rightarrow 0} \frac{1}{2\omega} \int dt d^3x e^{i\omega t} \langle [T_{ij}(x), T_{ij}(0)] \rangle$$



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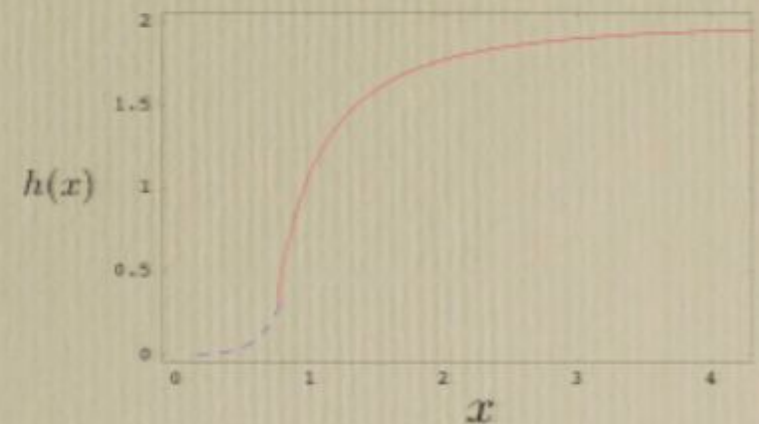
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The ratio is not corrected at order  $N_f/N_c$ . Therefore:

$$\eta = \frac{\pi}{8} N_c^2 T^3 \left[ 1 + \frac{\lambda}{8\pi^2} \frac{N_f}{N_c} h\left(\frac{\lambda T}{M_q}\right) + \dots \right]$$



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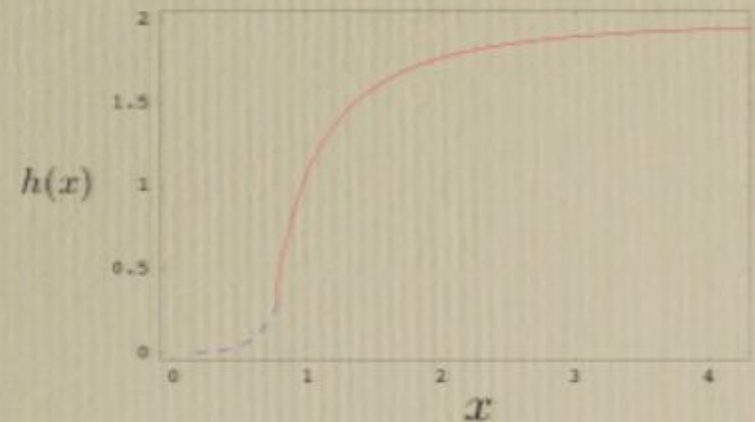
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Enhancement



Potential consequence for the  
“jet quenching” thermometer:

$$\hat{q} = c\sqrt{\lambda}T^3$$



## iv) Finite baryon density.

Kobayashi, D.M., Matsuura, Myers & Thomson

## Gauge theory

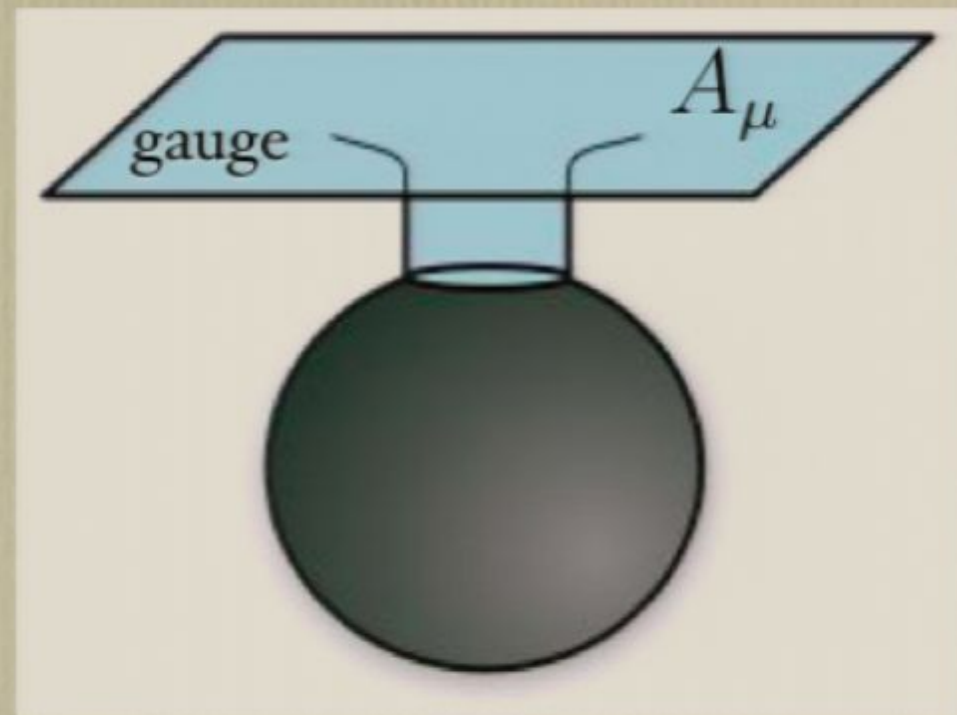
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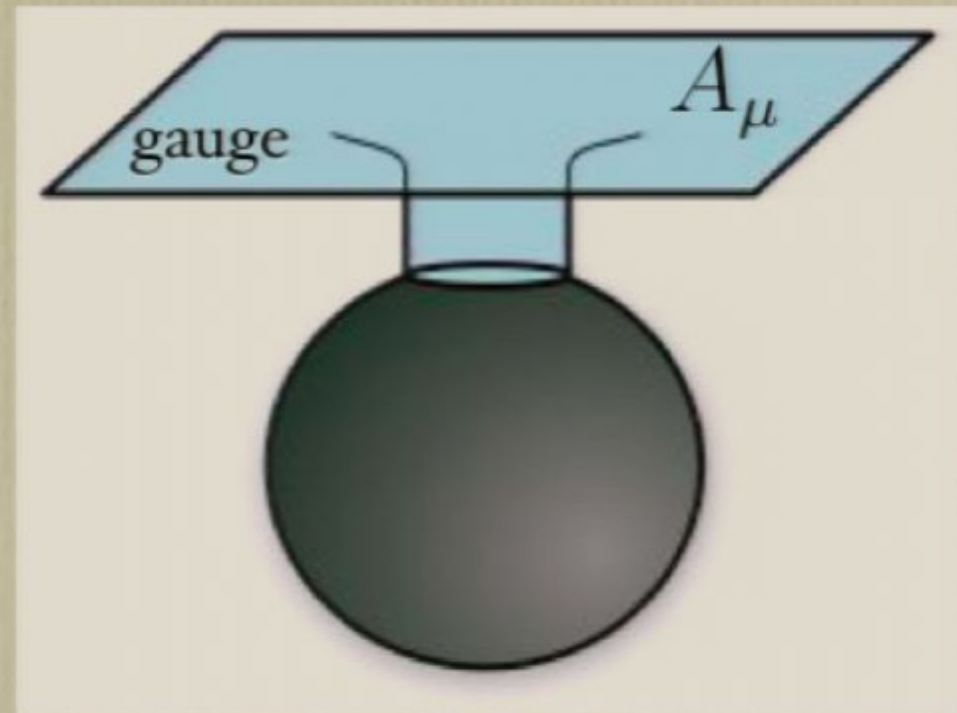
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$$H \rightarrow H + \mu_B J^0$$

$$\langle J^0 \rangle = n_B$$

## String theory

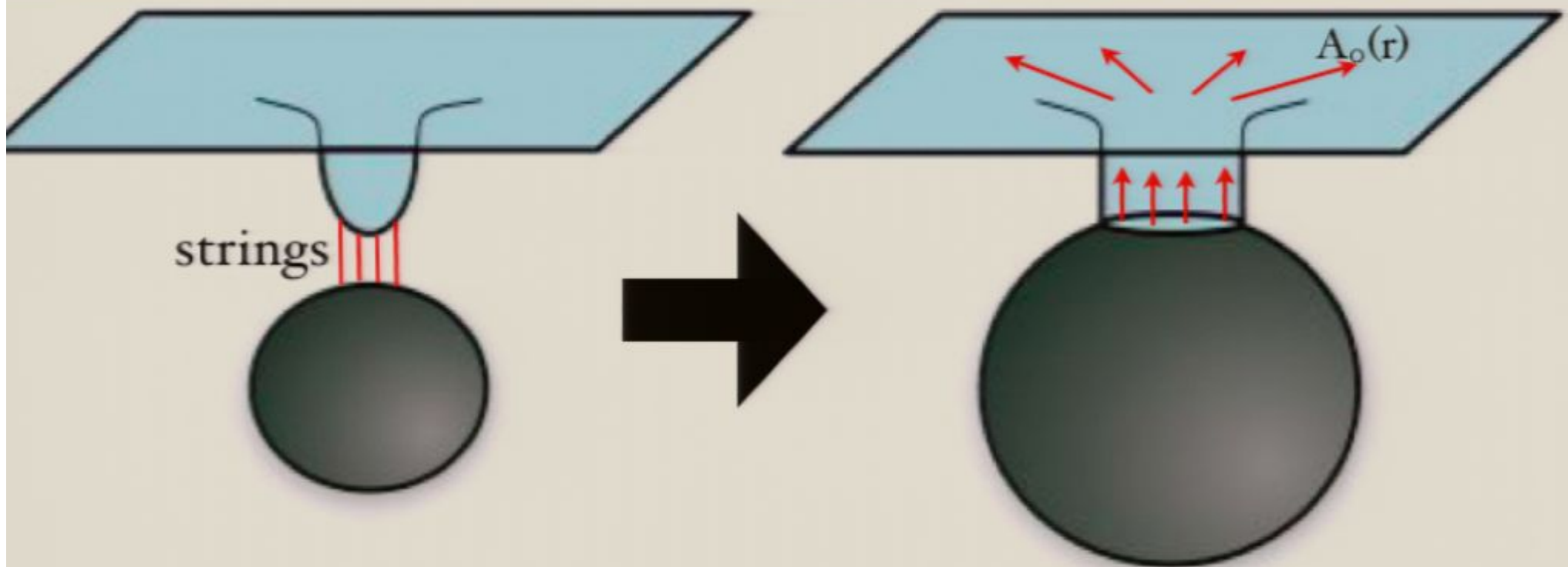
$N_f$  overlapping Dq-branes



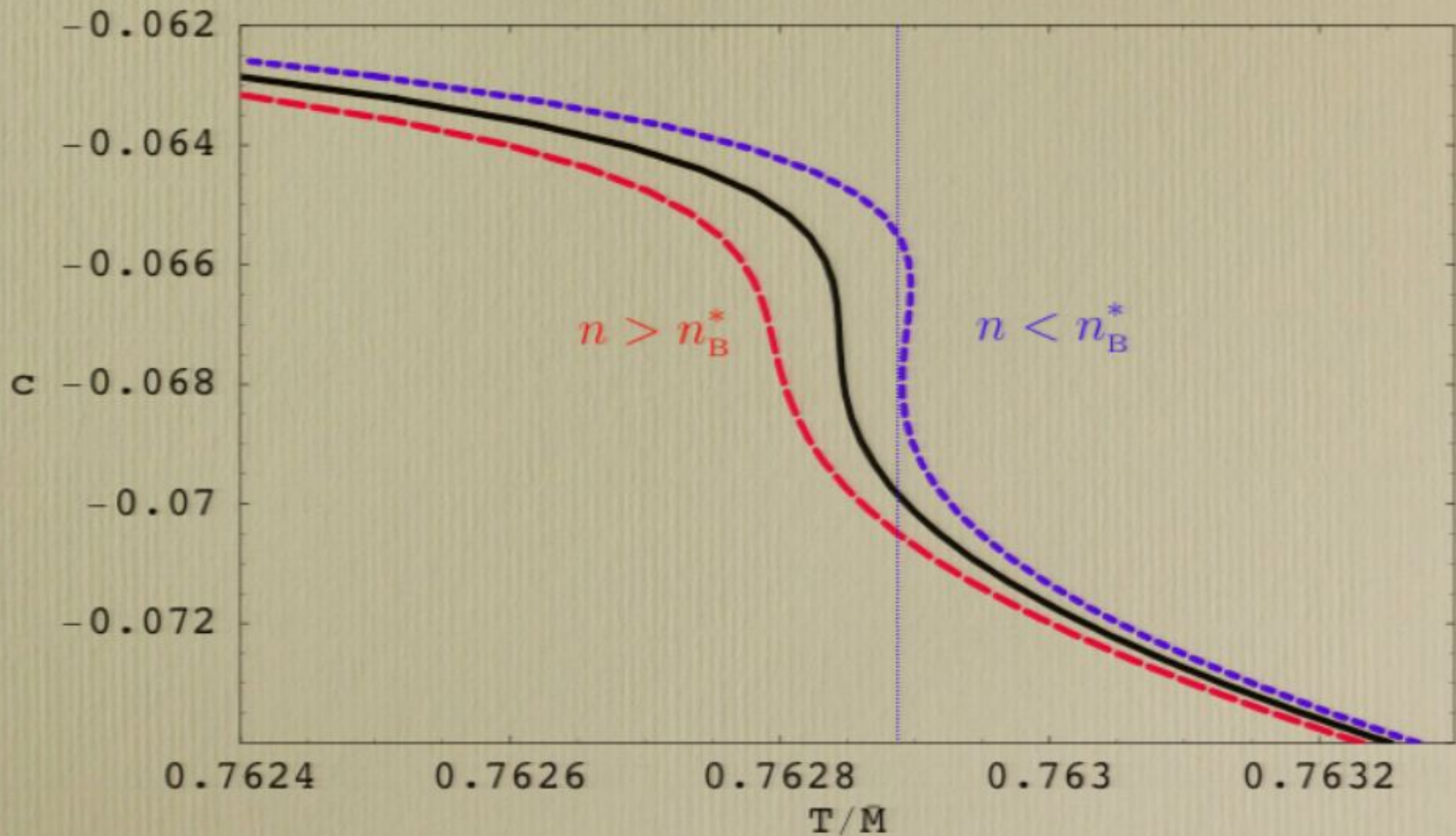
$$A_0 = \mu_B + \frac{n_B}{r^2} + \dots$$



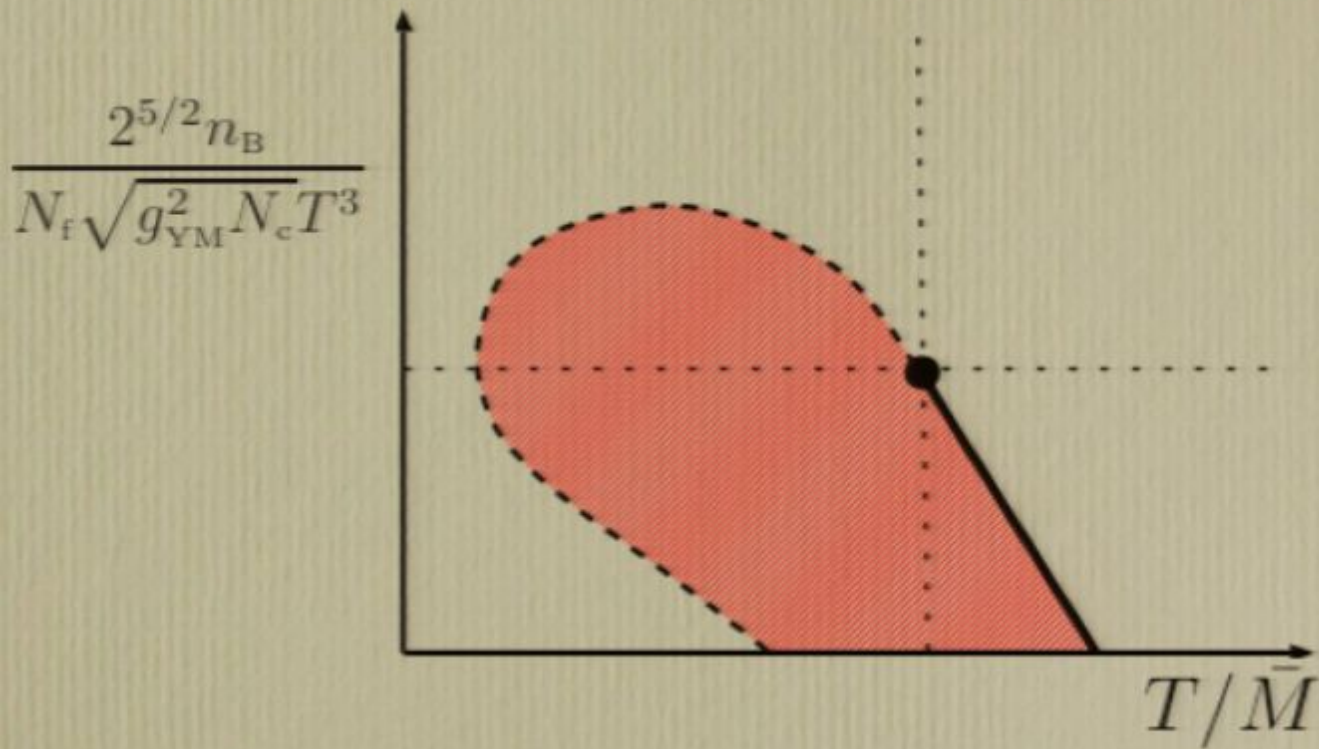
With finite density, all embeddings are of BH type:



# Transition persists up to $n_B^*$

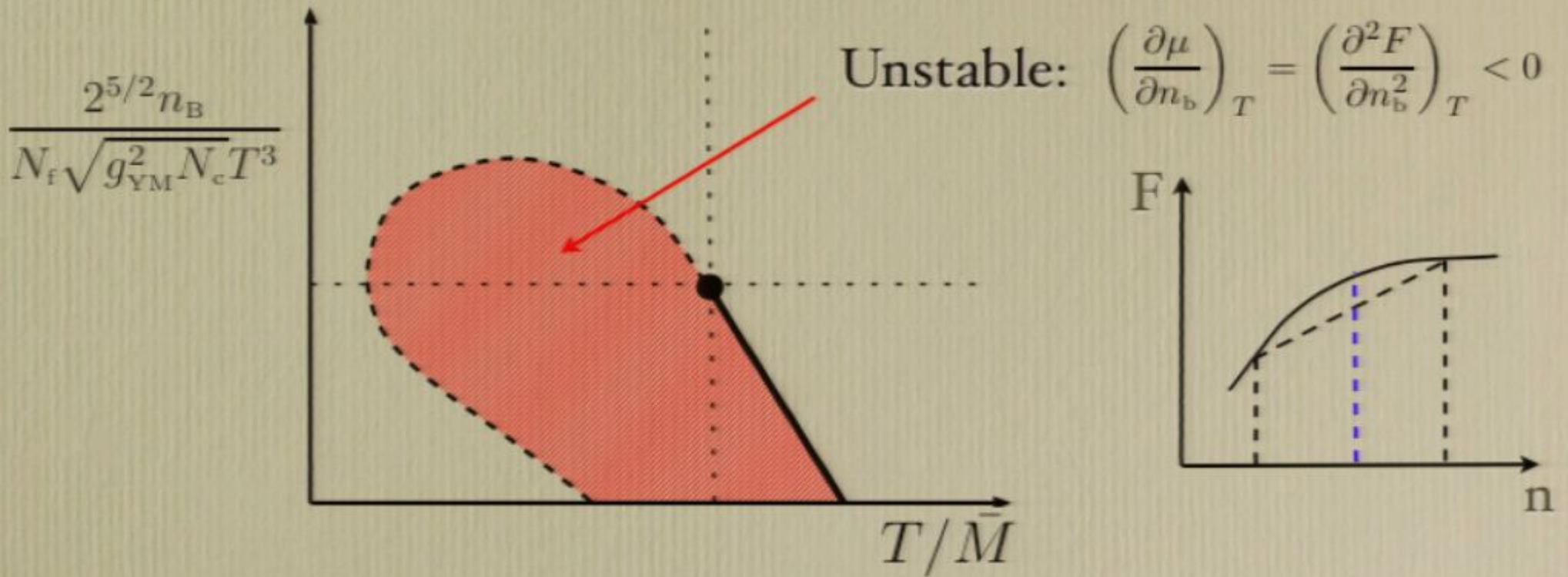


# Phase Diagram

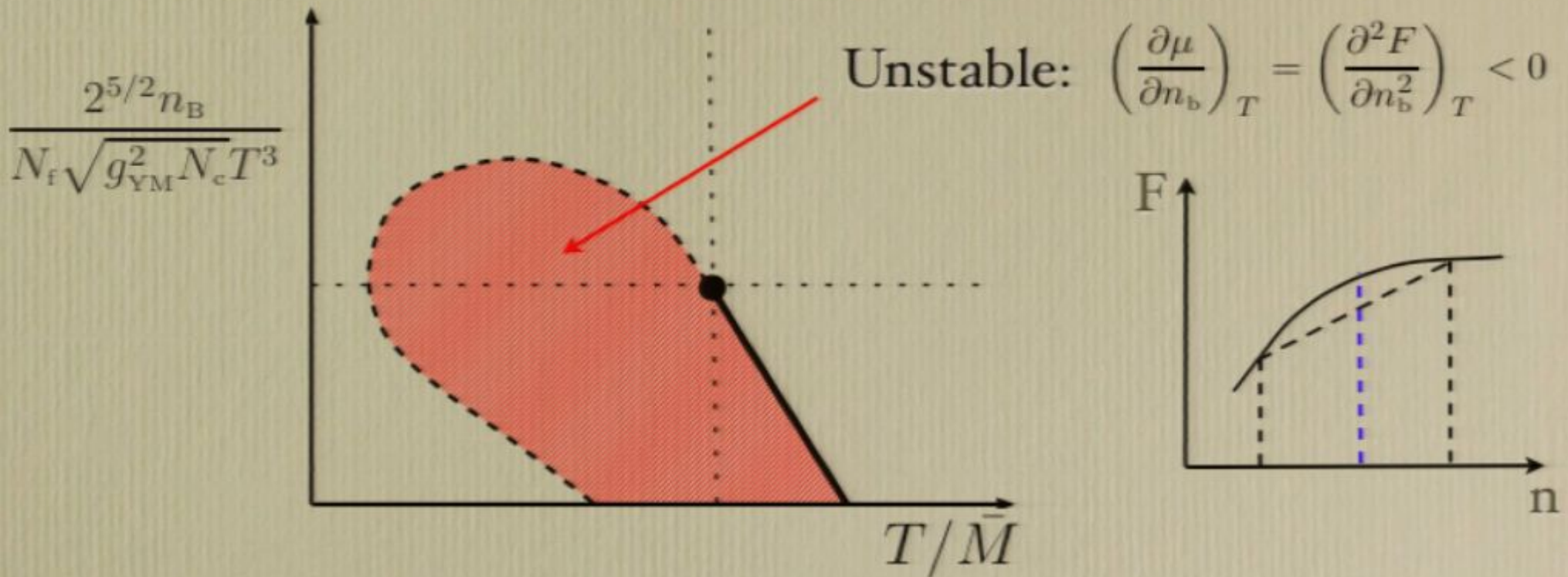




# Phase Diagram



# Phase Diagram



True ground state?

Inhomogeneous charge distribution  
(in different D-branes or in space),  
baryon vertex, ...

v) Future directions.



# Lots to do at finite density

- With charged scalars  $\rightarrow$  Bose-Einstein condensation (eg. spontaneous breaking of rotational symmetry)

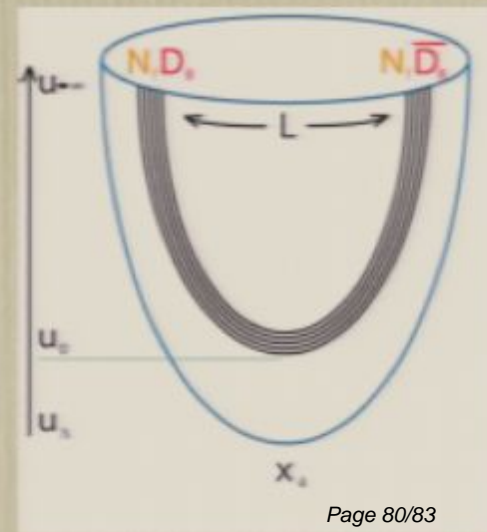
Cf. Miransky's talk

- Physics of the Fermi surface.
- Colour superconductivity vs. chiral waves:

$$\langle \bar{\psi}\psi(x) \rangle \sim e^{ik \cdot x}$$

- Need model with only fundamental fermions:

Sakai & Sugimoto



# Towards far from equilibrium

Horizons encode properties of QGPs:

- Static, eg  $S=A/4G$ . Gubser, Klebanov & Peet
- Near equilibrium, eg viscosity. Policastro, Son & Starinets  
Kovtun, Son & Starinets
- Far from equilibrium, eg. inhomogeneities, collective instabilities, dynamical evolution of the QGP fireball, etc.
- One strong motivation:  
Understand fast thermalisation of the QGP.



One conclusion:



One conclusion:

Work hard and be universal.