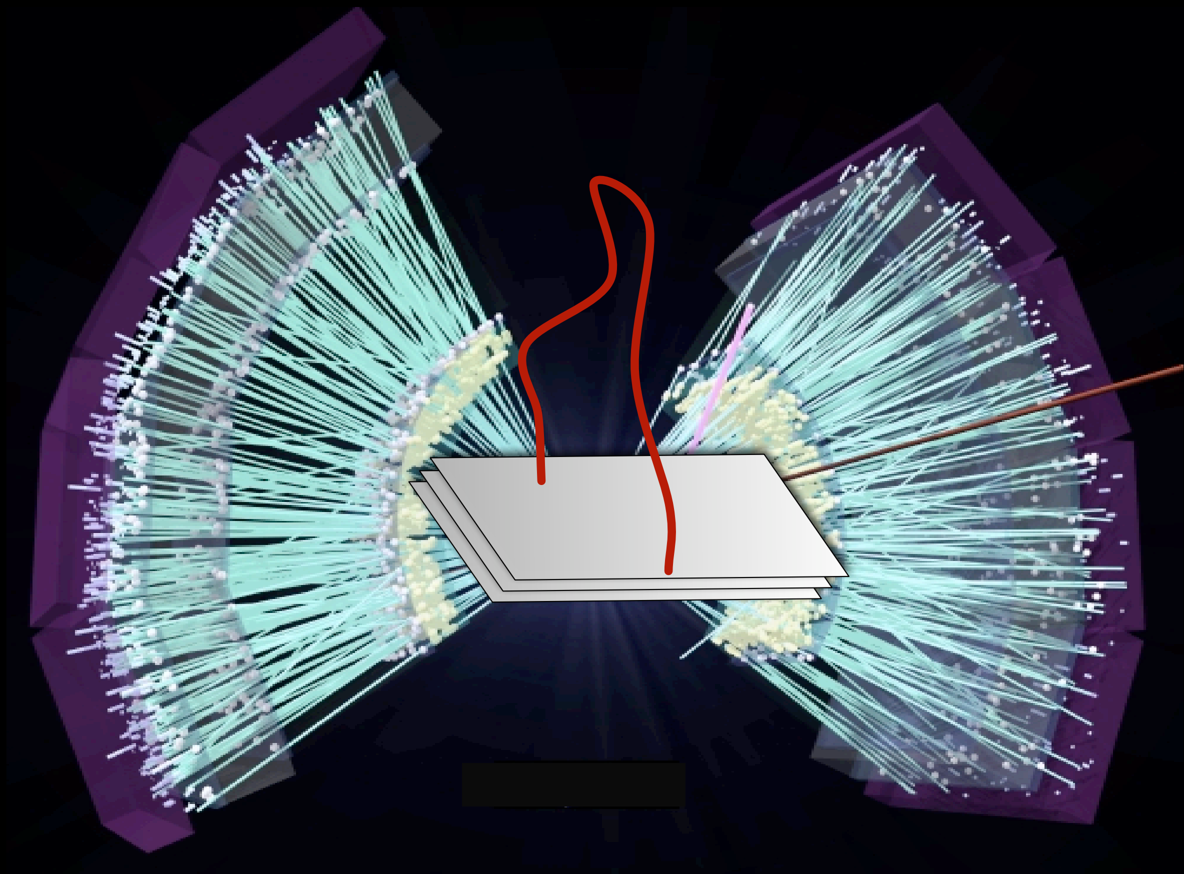
RHIC physics and String Theory: The Fundamental Story



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Plan

i) Motivation.

ii) Phase transitions.

iii) Viscosity.

iv) Photon production.

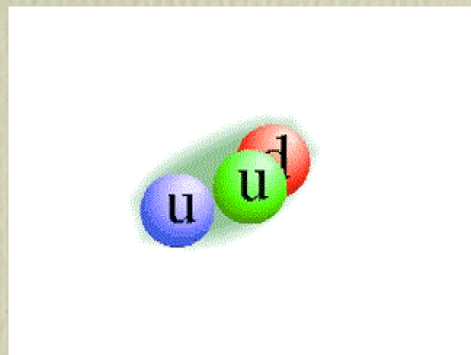
v) Finite density.

vi) Future prospects.

i) Motivation.

The QCD challenge

- QCD remains a challenge after 34 years!



The QCD challenge

- QCD remains a challenge after 34 years!
- A string reformulation might help.
- Lots of gauge/gravity examples.
- Unfortunately, QCD dual is not accessible via supergravity.

Therefore:

- Certain quantitative observables (eg. T=0 spectrum) will require going beyond supergravity.

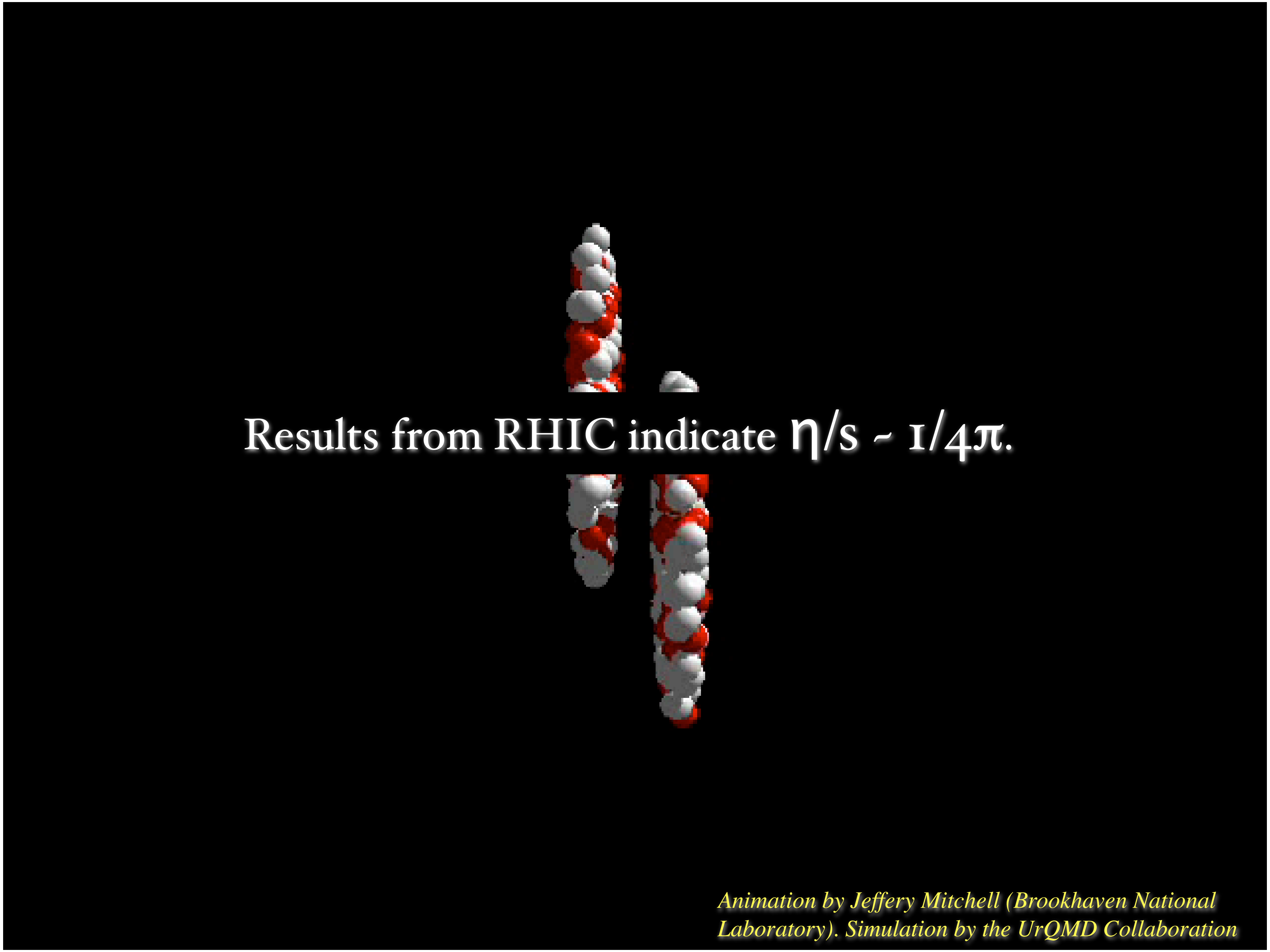
- However, certain predictions may be universal enough to apply in certain regimes.

- Good example: $\eta/s = 1/4\pi$

  Gubser, Klebanov & Peet '96
  Policastro, Son & Starinets '01

  Same for all non-Abelian plasmas with gravity dual!

- How about QCD just above deconfinement?


Results from RHIC indicate η/s ~ 1/4π.
Animation by Jeffery Mitchell (Brookhaven National Laboratory). Simulation by the UrQMD Collaboration

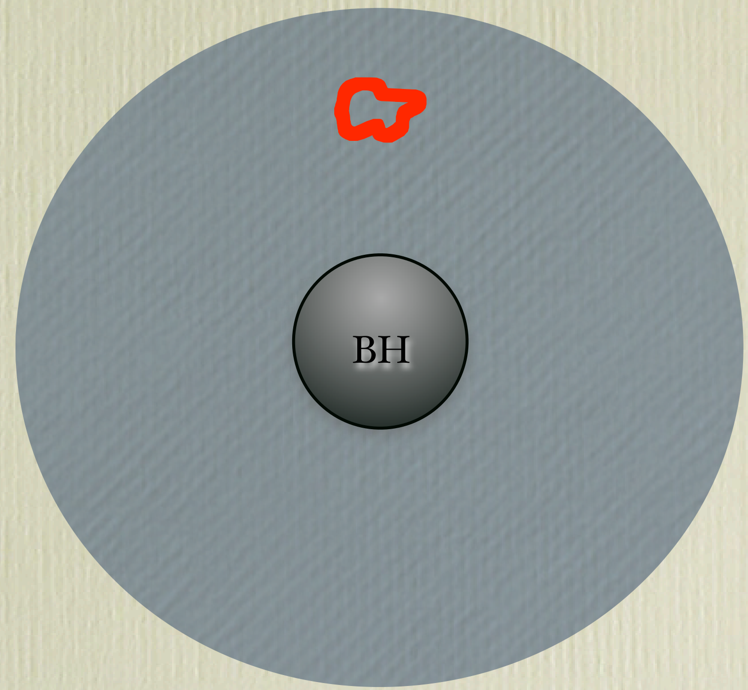
Observations:

- Did not know η/s was going to be universal!

Kovtun, Son & Starinets '03

- Based on universal property:

  Gravity dual of a deconfined plasma contains a black hole



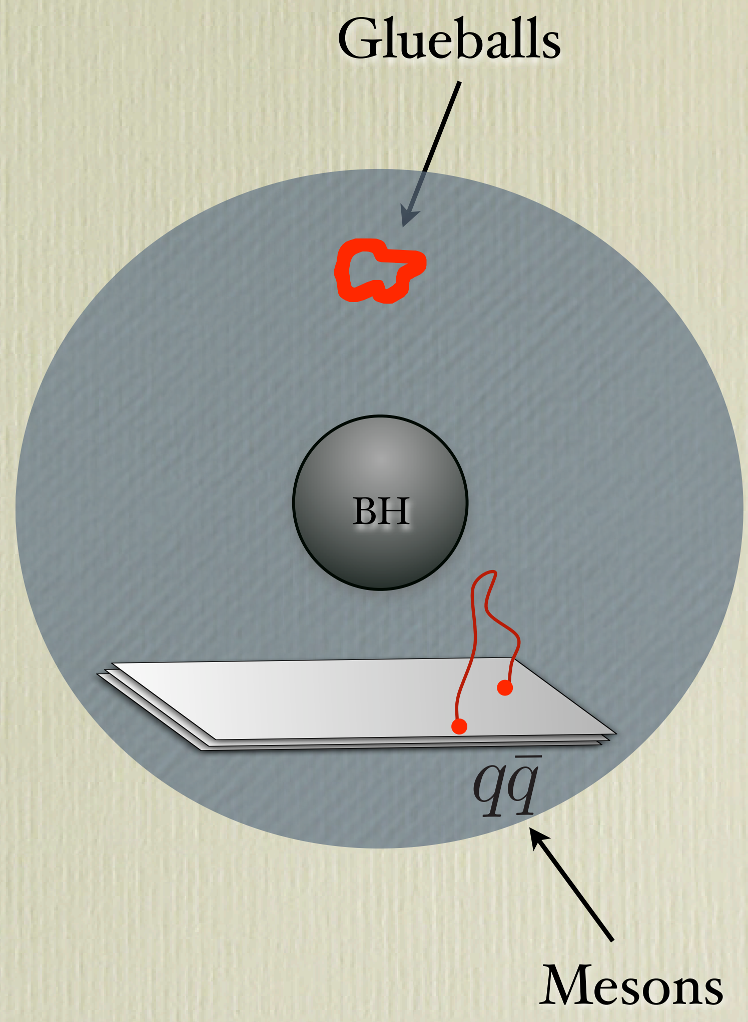
Observations:

- Combine with another one:

$N_f << N_c$ quark flavours correspond to N_f probe branes

Karch & Katz '02

For concreteness will concentrate on D7 probes in D3 background.



Disclaimer:

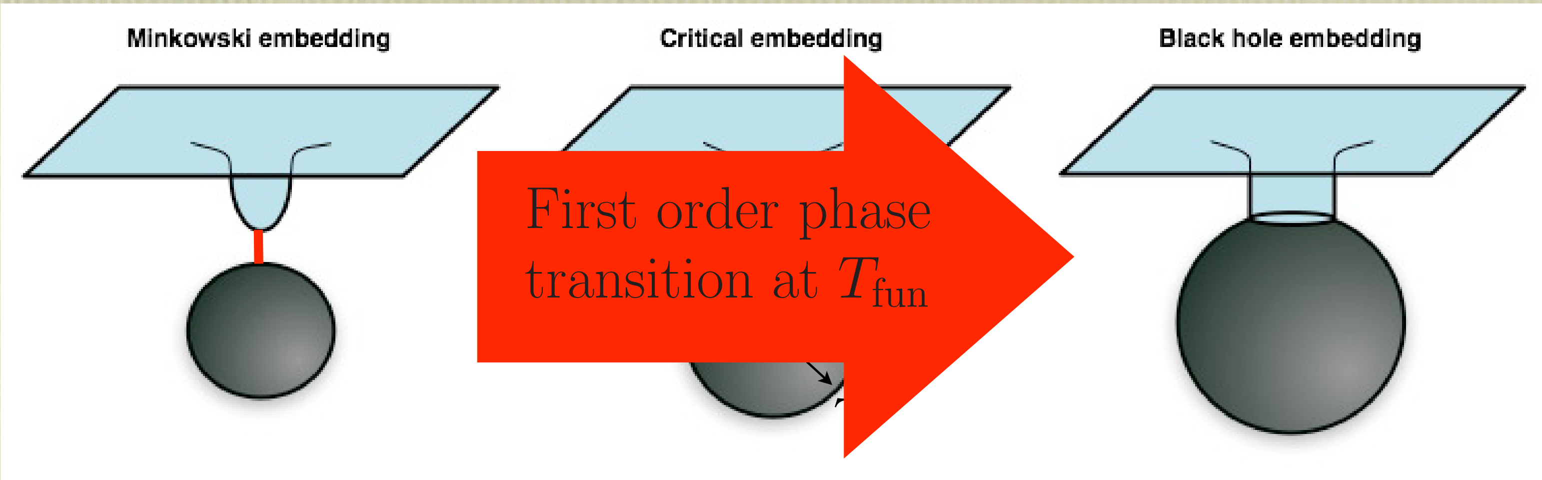
Not QCD, so interpret with caution.

ii) Fundamental phase transitions.

D.M., Myers & Thomson ‘06

Previous related work:

Babington, Erdmenger, Guralnik & Kirsch ’03
Kruczenski, D.M., Myers & Winters ‘03
Kirsch ‘04



- Discrete set of mesons with mass gap:

$$M_{\text{mes}} \sim \frac{M_{\text{q}}}{\sqrt{\lambda}} \sim T_{\text{fun}}$$

- Free massive quarks.
- Absolutely stable -- survive deconfinement!
- No quasi-particle excitations!
- In good agreement with lattice QCD, eg. for J/Ψ:

Lattice: $T_{\text{fun}} \simeq (317 - 403)\ \text{MeV}$

Gravity: $T_{\text{fun}} \simeq (371 - 712)\ \text{MeV}$

iii) Viscosity of fundamental matter.

D.M., Myers & Thomson ‘06

Universal viscosity bound

- Conjectured universal bound for relativistic plasmas:

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

Kovtun, Son & Starinets '03

- Saturated at $N_c \to \infty$, $\lambda \to \infty$ by all holographic theories with adjoint matter.

- Results from RHIC are close: $\frac{\eta}{s} \sim \frac{1}{4\pi}$

Teaney '03
Shuryak '03
Romatschke & Romatschke '07
Heinz '07

- What about when quarks are included? QCD and leading N_f/N_c correction.

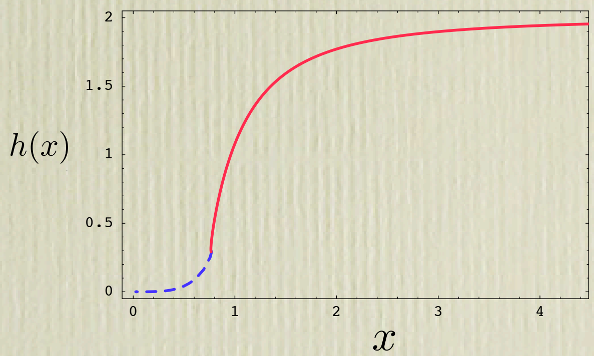
Holographic calculation

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

Couples to g_{ij} → $\eta \sim \frac{\delta^2 S_{\mathrm{D7}}}{\delta g_{ij}^2}$

- η and S are corrected at $\mathcal{O}\left(\frac{N_{\mathrm{f}}}{N_{\mathrm{c}}}\right)$ but the ratio is not!

$$\eta = \frac{\pi}{8} N_{\mathrm{c}}^2 T^3 \left[1 + \frac{\lambda}{8\pi^2} \frac{N_{\mathrm{f}}}{N_{\mathrm{c}}} h\left(\frac{\lambda T}{M_{\mathrm{q}}}\right) + \cdots \right]$$



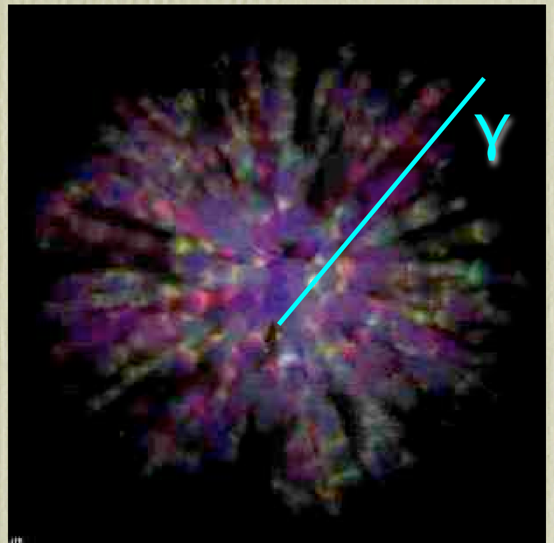
Universal enhancement with simple origin: $G_{\mathrm{N}} T_{\mathrm{D7}} \sim \frac{\lambda N_{\mathrm{f}}}{N_{\mathrm{c}}}$

iv) Holographic photon production.

D.M., Patiño-Jaidar (to appear)

Why photons?

- QGP is optically thin → Photons carry valuable information.



- Holographic results for massless matter:

Caron-Huot, Kovtun, Moore, Starinets & Yaffe '06

Parnachev & Sahakian '06

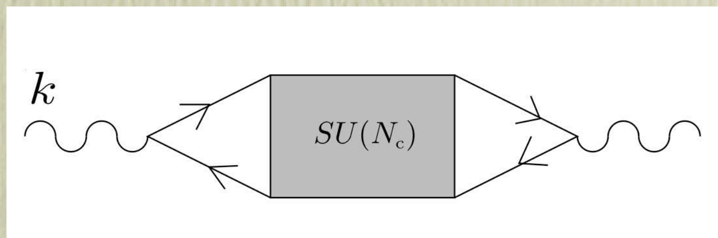
- To leading order in the electromagnetic coupling constant:

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

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

$\chi_{\mu\nu}(k) = -2\,\mathrm{Im}\, G^{\mathrm{R}}_{\mu\nu}(k)$ is the spectral density

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



Holographic calculation

<u>Gauge theory</u>

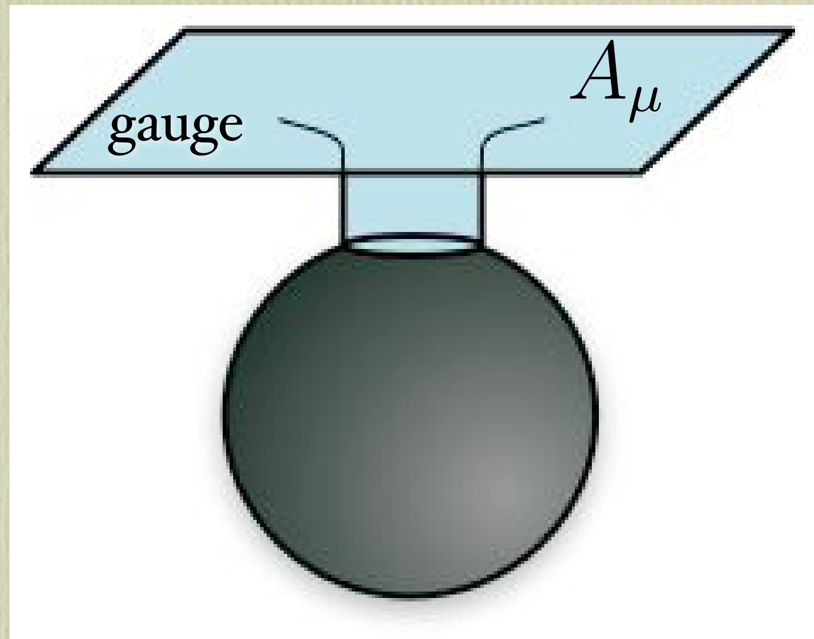
$$U(N_{\rm f}) \simeq SU(N_{\rm f}) \times U(1)_{\rm B}$$

Conserved $J_\mu^{\rm B} = J_\mu^{\rm EM}$

AdS/CFT prescription:

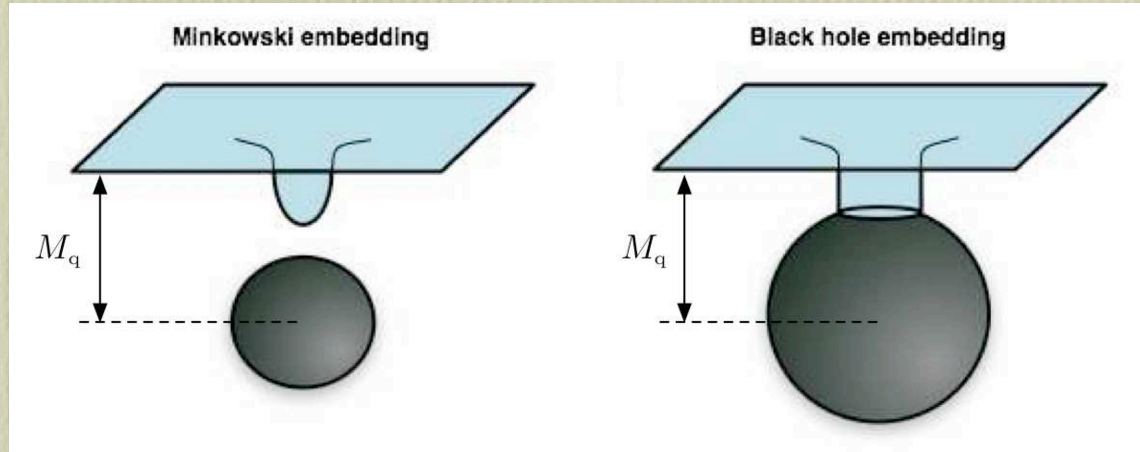
$$G^{\rm R}_{\mu\nu} \sim \frac{\delta^2 S_{\rm D7}}{\delta A_\mu \delta A_\nu}$$

<u>String theory</u>



Comments:

- Concentrate on BH embeddings:



$$\chi = \sum \text{delta functions}$$

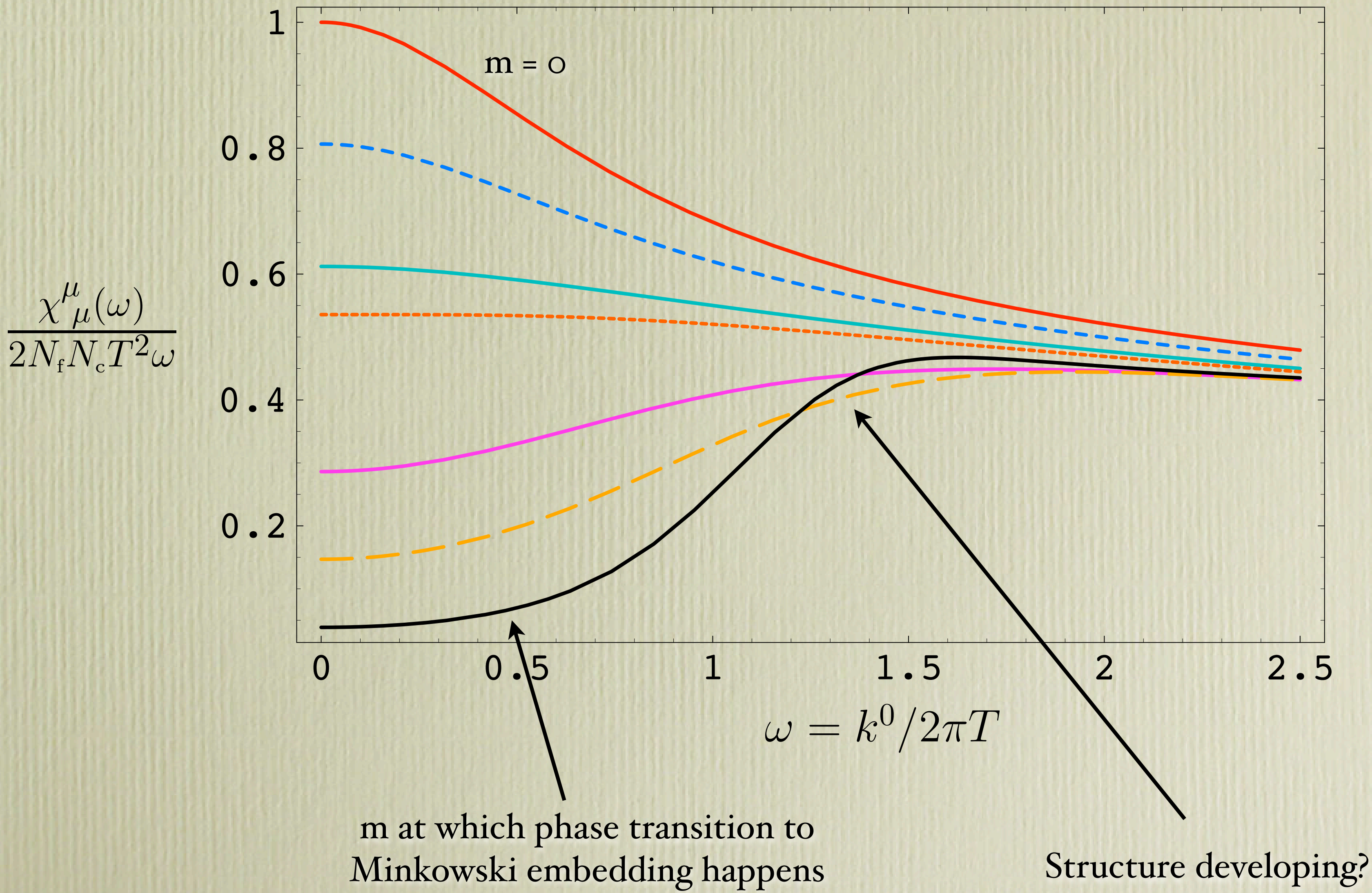
- No obvious comparison of M_q-dependence to pQCD:

Arnold, Moore & Yaffe '01

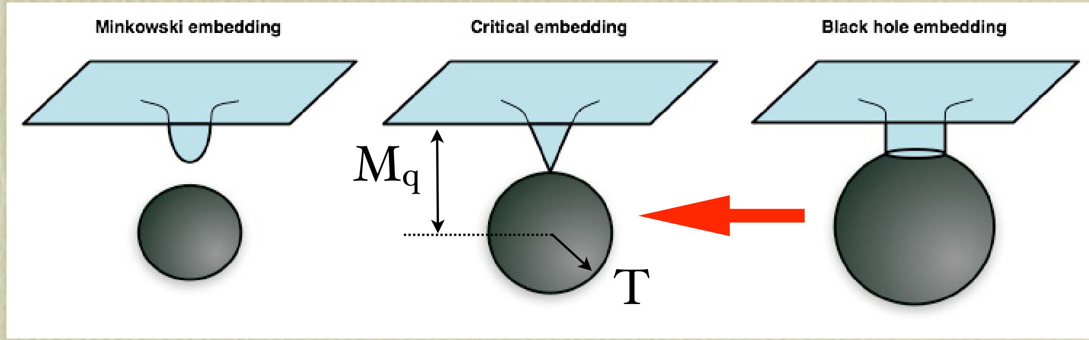
$$M_{\text{thermal}} \sim \sqrt{\lambda} T \gg M_q$$

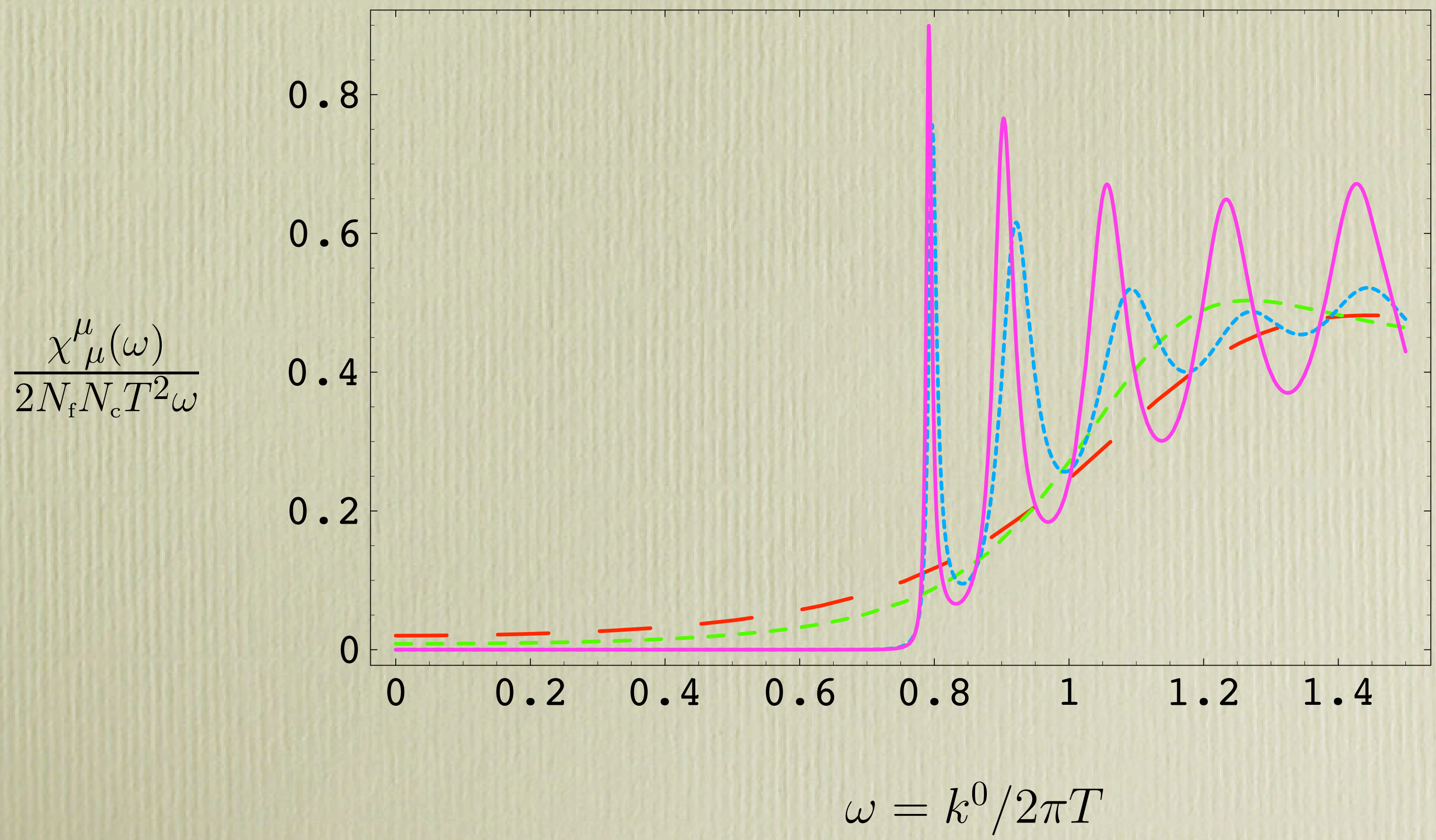
But this assumes existence of quasi-particles!

Spectral function for constant $m \sim \frac{M_{\rm mes}}{T} \sim \frac{M_{\rm q}}{\sqrt{\lambda}T}$



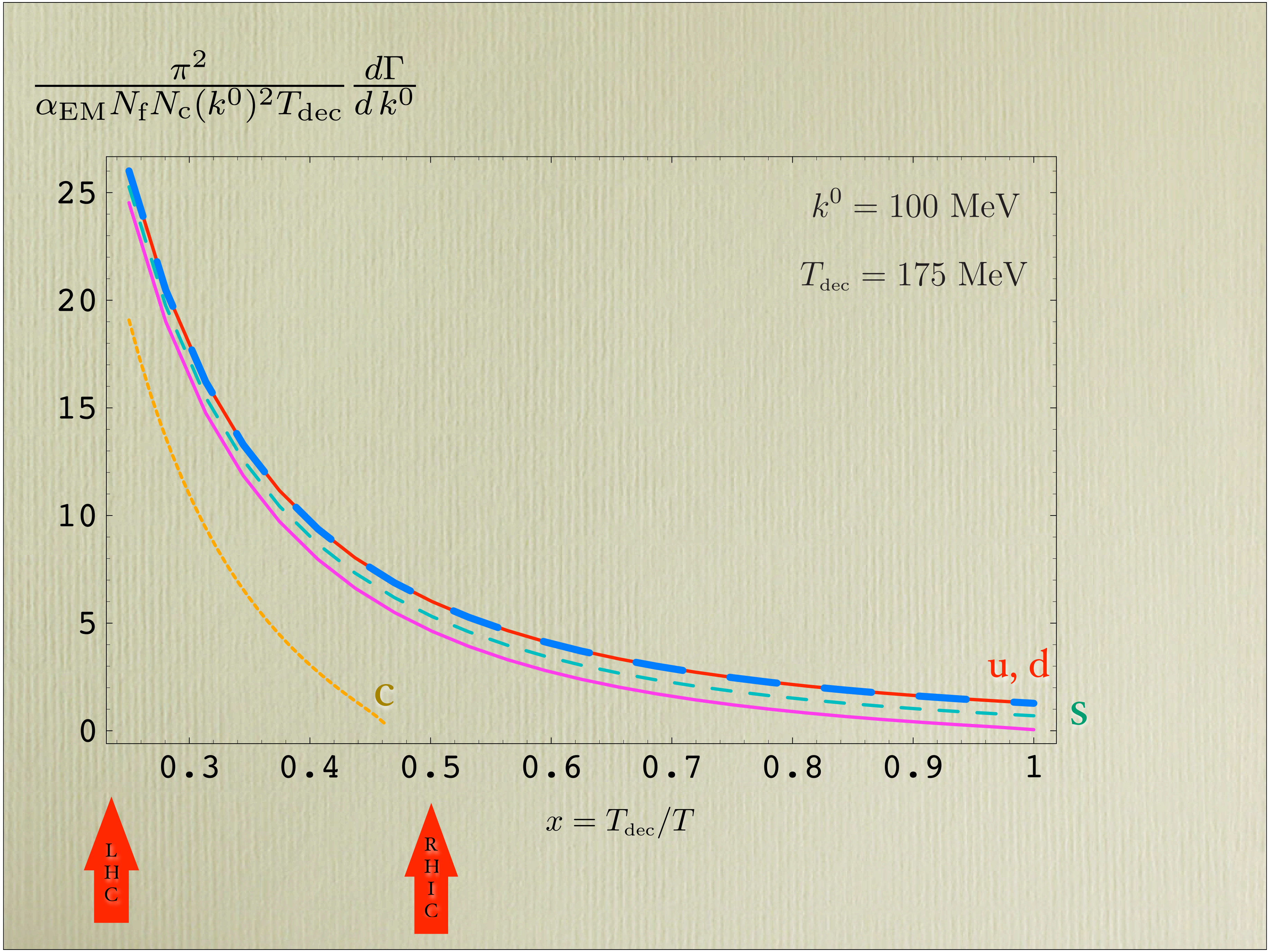
Approaching the critical embedding:

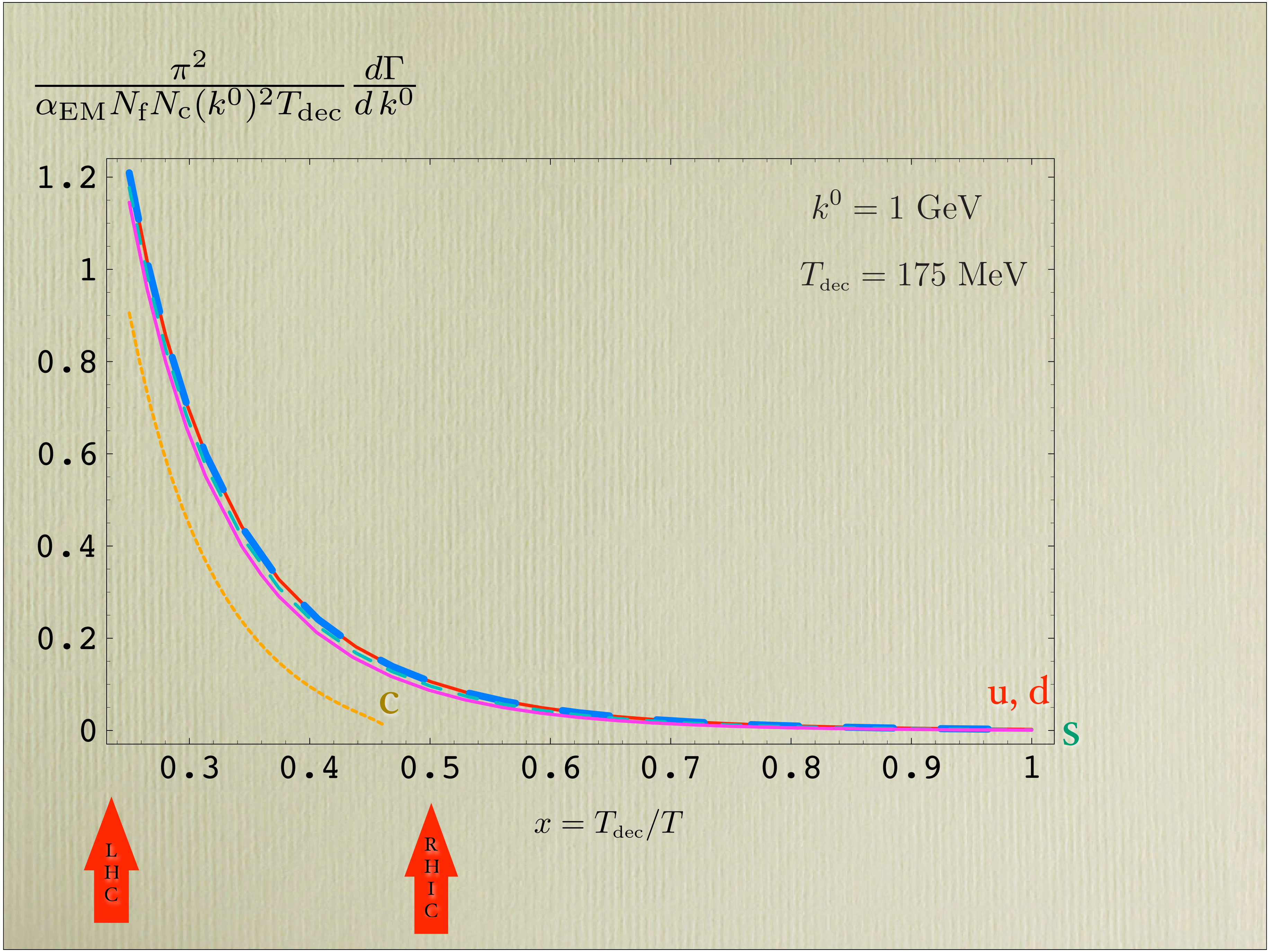




To compare with experiment

- Calculate photon production rate:


$\frac{\pi^2}{\alpha_{\rm EM} N_{\rm f} N_{\rm c} (k^0)^2 T_{\rm dec}} \frac{d\Gamma}{d\,k^0}$
$k^0 = 100$ MeV
$T_{\rm dec} = 175$ MeV
25
20
15
10
5
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
u, d
s
c
$x = T_{\rm dec}/T$
LHC
RHIC



$\frac{\pi^2}{\alpha_{\rm EM} N_{\rm f} N_{\rm c} (k^0)^2 T_{\rm dec}} \frac{d\Gamma}{d\,k^0}$
$k^0 = 1$ GeV
$T_{\rm dec} = 175$ MeV
1.2
1
0.8
0.6
0.4
0.2
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
c
u, d
s
$x = T_{\rm dec}/T$
LHC
RHIC

To compare with experiment

- Plug into hydrodynamic simulation of spacetime evolution of the plasma.
- Experimentally distinguish different sources: QGP photons, prompt photons, decay photons, etc.

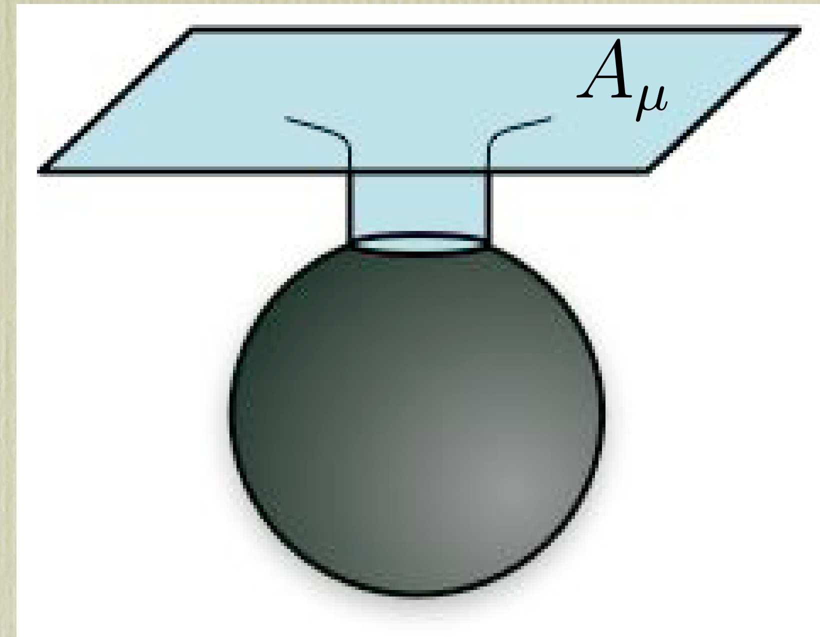
v) Finite baryon density.

Kobayashi, D.M., Matsuura, Myers & Thomson '06

Gauge theory | String theory

$U(N_\mathrm{f}) \simeq SU(N_\mathrm{f}) \times U(1)_\mathrm{B}$

Conserved J_μ



$H \to H + \mu_\mathrm{B} J^0$

$\langle J^0 \rangle = n_\mathrm{B}$

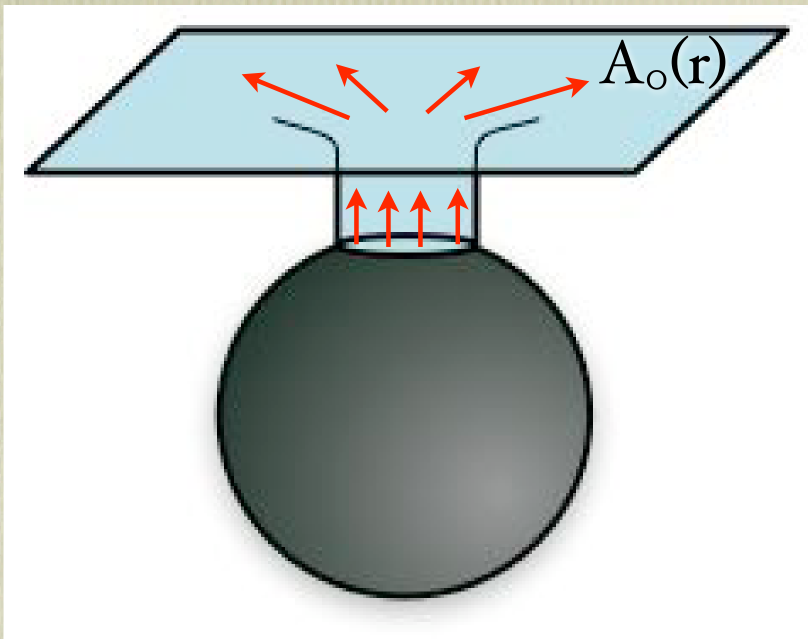
$$A_0 = \mu_\mathrm{B} + \frac{n_\mathrm{B}}{r^2} + \cdots$$

Gauge theory

String theory

$U(N_{\rm f}) \simeq SU(N_{\rm f}) \times U(1)_{\rm B}$

Conserved J_μ

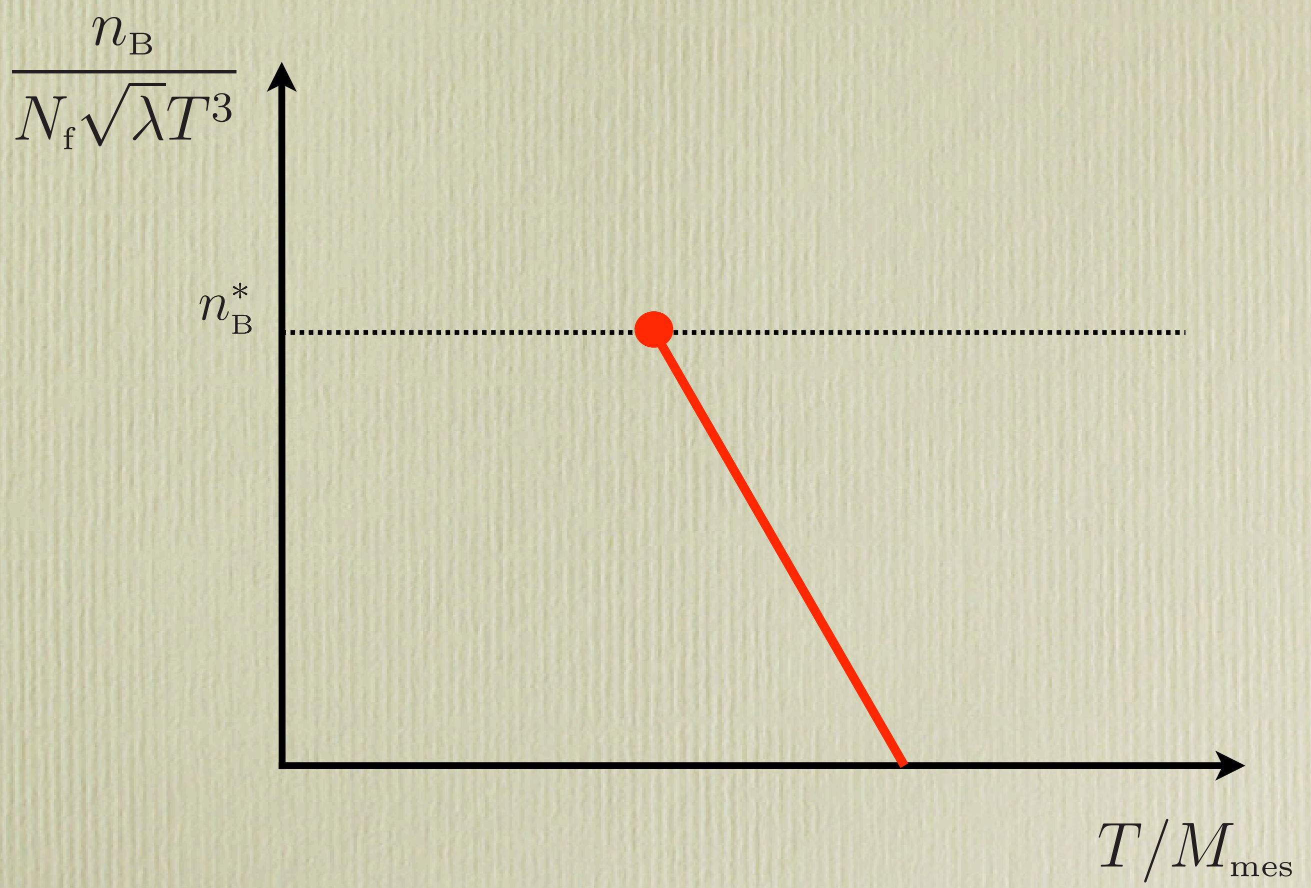


$$H \to H + \mu_{\rm B} J^0$$

$$\langle J^0 \rangle = n_{\rm B}$$

$$A_0 = \mu_{\rm B} + \frac{n_{\rm B}}{r^2} + \cdots$$

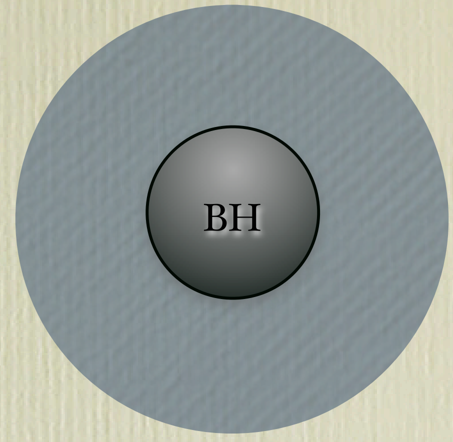
Phase Diagram



vi) Future prospects.

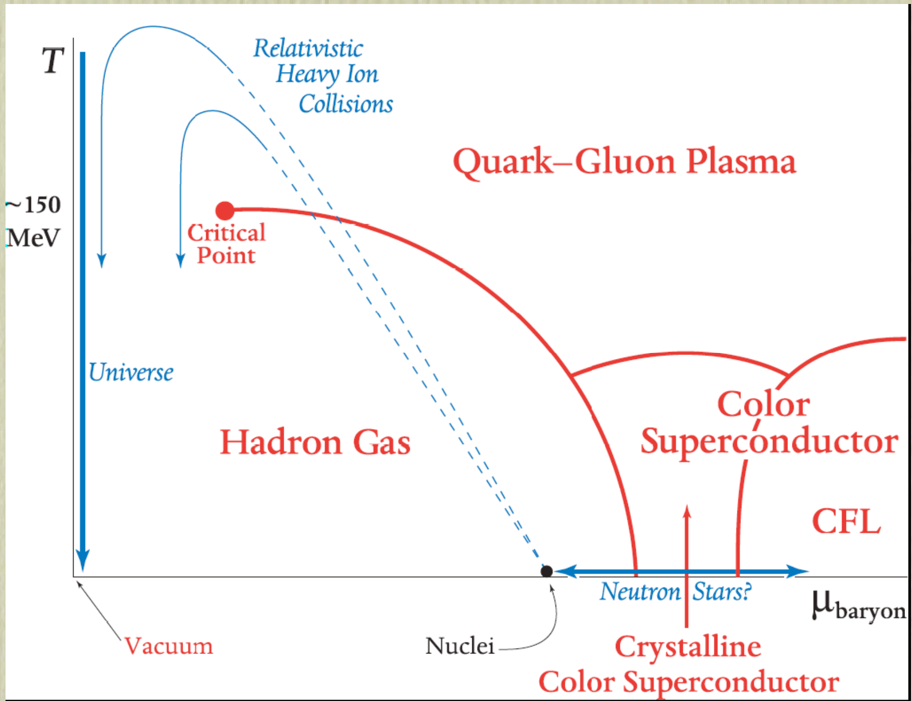
Towards far from equilibrium

Horizons encode properties of QGPs:



- Static → Thermodynamics: S=A/4G.
- Small perturbations → Near equilibrium, eg. transport coefficients.
- Large perturbations → Far from equilibrium, eg. collective instabilities.

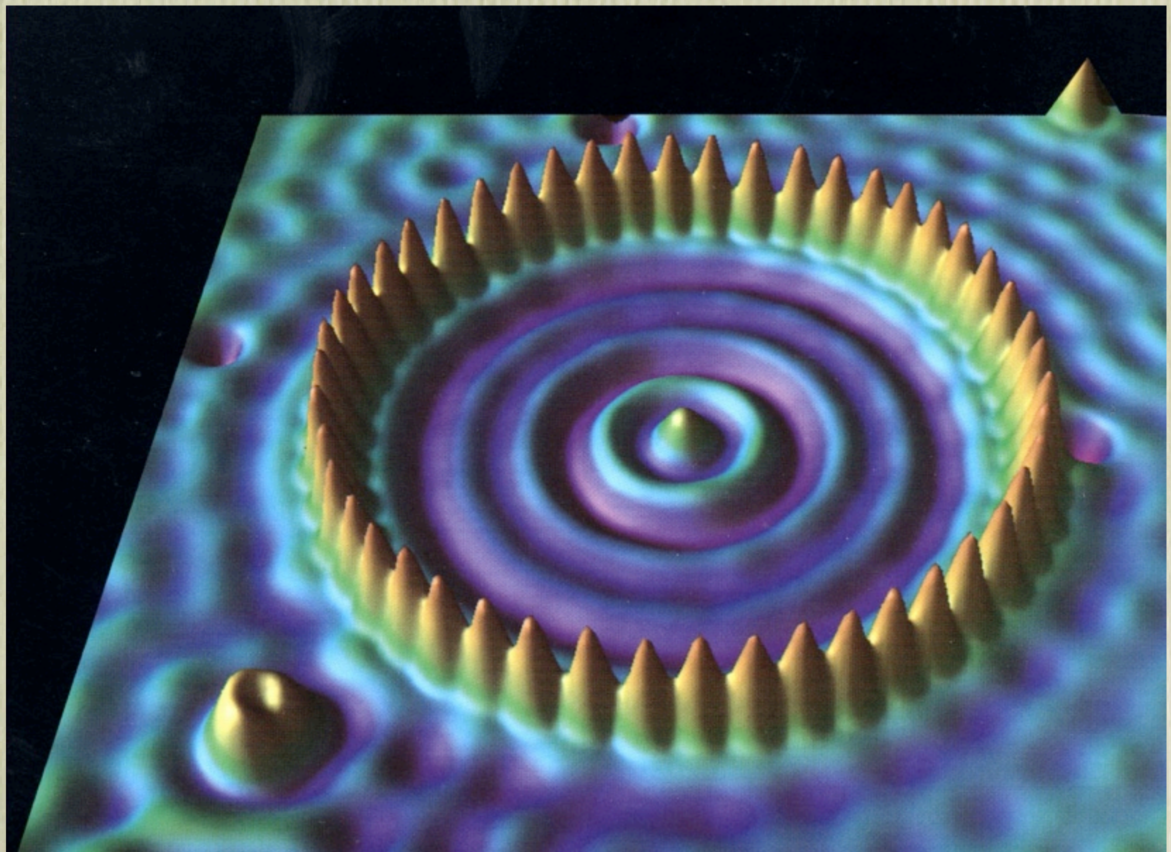
Lots to do at finite density



Caveats: Scalar fields (but not always) and large N_c.

Sakai & Sugimoto

Towards holographic condensed matter



Herzog, Kovtun, Sachdev & Son '07
Hartnoll & Kovtun '07
Hartnoll, Kovtun, Mueller & Sachdev '07

Heavy ion collisions at LHC

$T_{RHIC} \sim 2T_{dec}$, $T_{LHC} \sim 4T_{dec}$

Thank you.