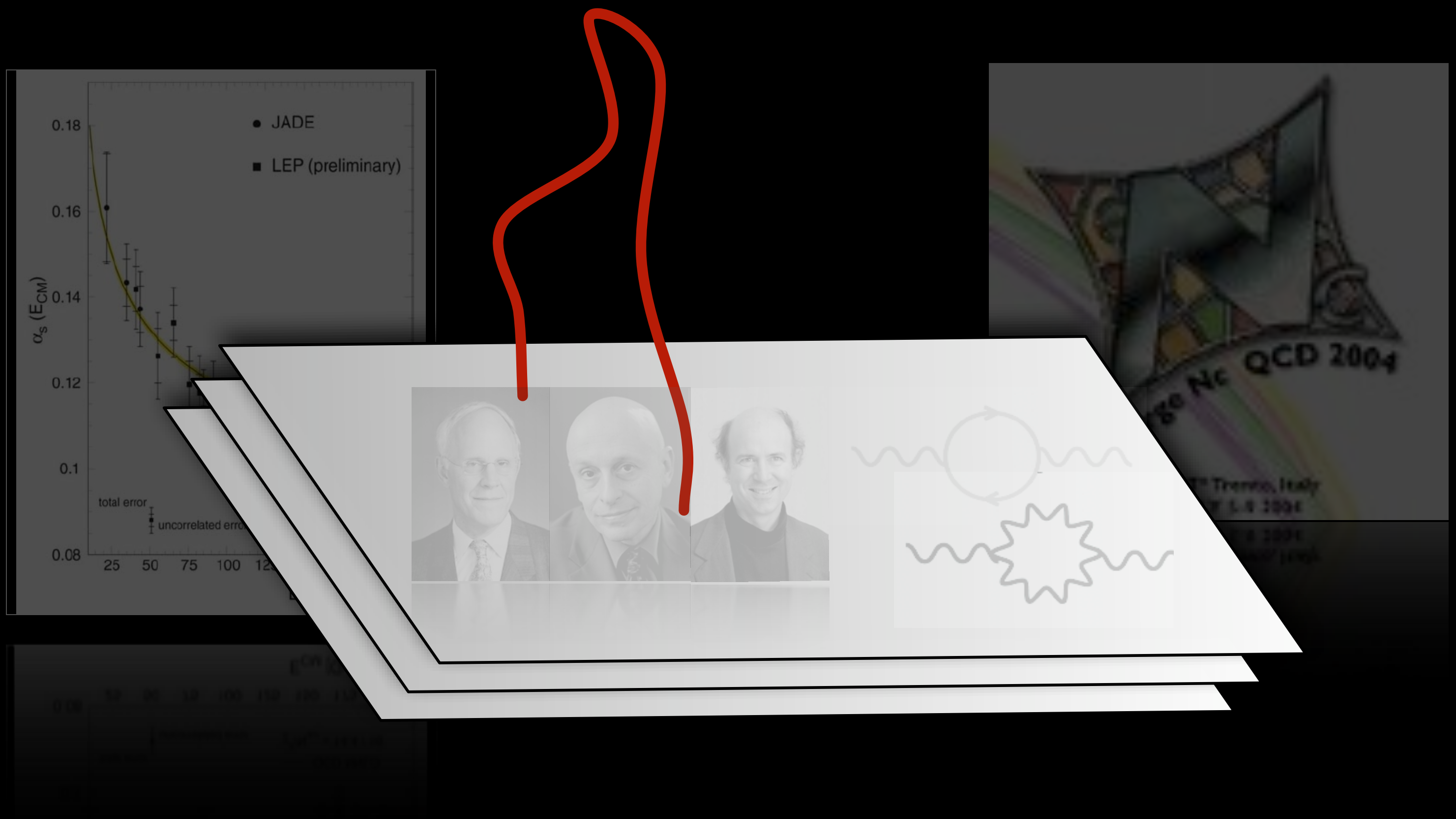
Strings & QCD: A review

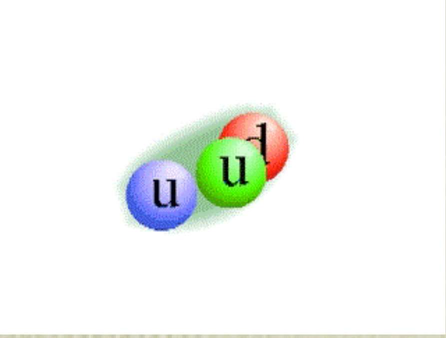


David Mateos

ICREA & University of Barcelona

The QCD challenge

- QCD remains a challenge after 36 years!



The QCD challenge

- QCD remains a challenge after 36 years!
- No analytic and truly systematic methods.
- Lattice is good for static properties, but not for real-time physics...
- ... and for a theorist it is a black box.

The QCD challenge

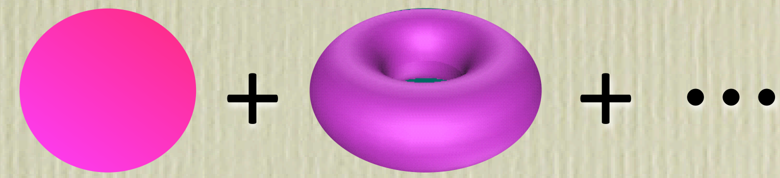
- A string reformulation might help -- topic of this talk.
- Not exhaustive, but hopefully clear picture.
- I apologize in advance for my personal biasses ...
- ... and for possible omissions of relevant references.

Focus on the dynamics of quarks and mesons:

- Responsible for almost all we know about QCD phenomenologically.
- Great progress on the string side in recent years.
- Personal bias.
- It is what Michael asked me to do.

The gauge/string duality

- Large-N_c expansion:

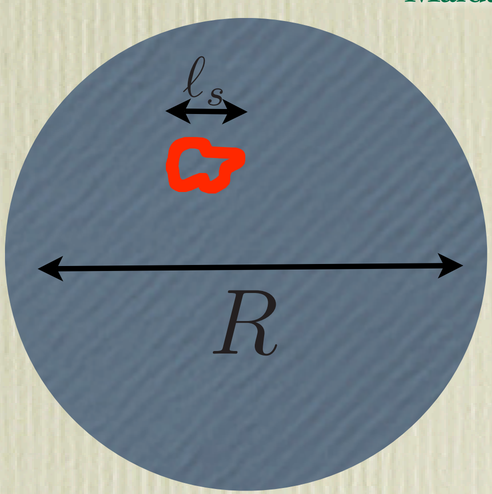


't Hooft '74

$$g_s = \frac{1}{N_c}$$

- First concrete example:

Maldacena '97



$$\mathcal{N} = 4 \text{ SYM} \quad \leftrightarrow \quad \text{IIB on } AdS_5 \times S^5$$

$$g_s = \frac{1}{N_c} \quad , \qquad R^4 = \lambda \ell_s^4$$

$$\lambda \equiv g_{\rm YM}^2 N_c$$

- Solvable string limit: $N_c \to \infty \, , \lambda \to \infty$

  Framework for non-perturbative gauge theory physics!

Why have we not solved QCD?

$$\Lambda_{\rm QCD} \sim M \exp\left(-\frac{\#}{g^2_{\rm YM}(M) N_{\rm c}}\right)$$

Decoupling: $g^2_{\rm YM}(M) N_{\rm c} \ll 1$

Supergravity: $g^2_{\rm YM}(M) N_{\rm c} \gg 1$

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

- Universal ratio: $\frac{\eta}{s} = \frac{1}{4\pi}$

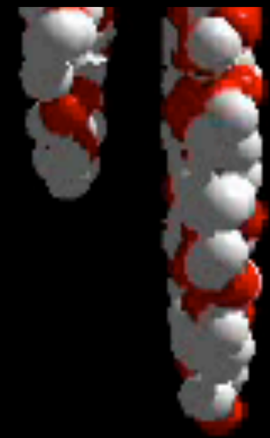
Policastro, Son & Starinets '01
Kovtun, Son & Starinets '03

- Same for all non-Abelian plasmas with gravity dual in the limit $N_c \to \infty \, , \lambda \to \infty$:

  - Theories in different dimensions.
  - With or without fundamental matter.
  - With or without chemical potential, etc.

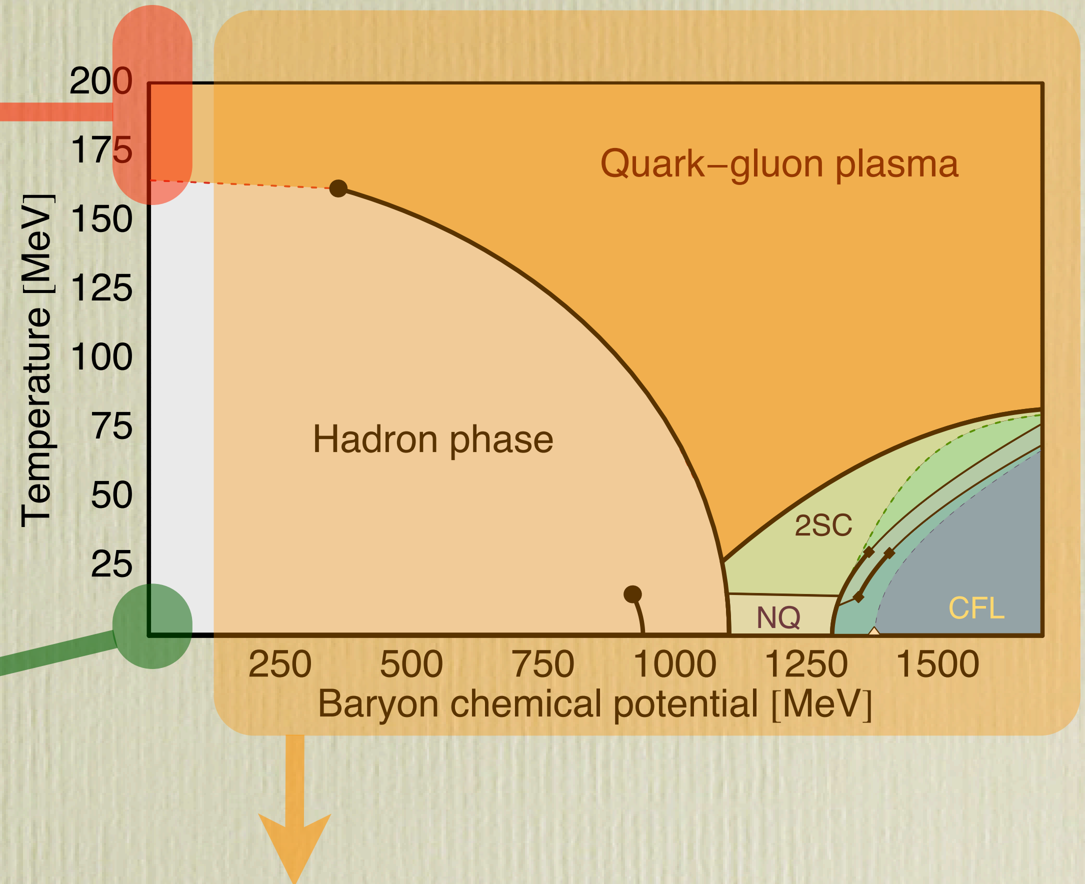
- How about QCD just above deconfinement?

Results indicate strong coupling and $\frac{\eta}{s} \sim \frac{1}{4\pi}$.



Animation by Jeffery Mitchell (Brookhaven National Laboratory). Simulation by the UrQMD Collaboration

Plan for the rest of the talk: As in the QCD phase diagram



Focus on deconfined phase at $T > T_c\ ,\ \ \mu_B = 0$.

- Experimentally studied in HIC.
- Greatest impact from string theory (eg. viscosity/entropy ratio).

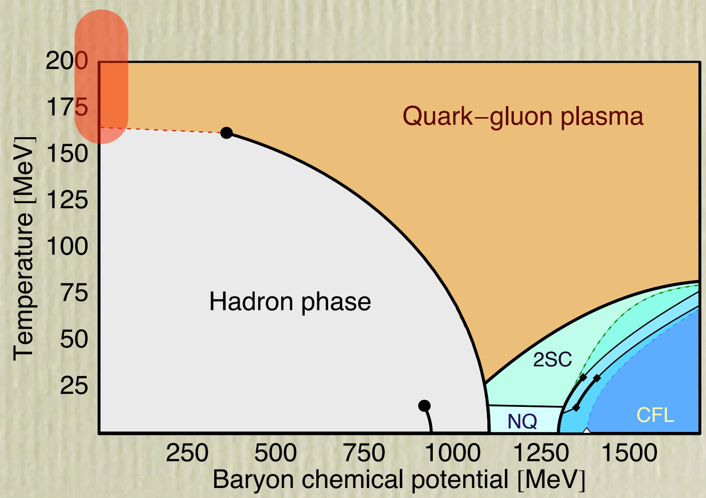
More briefly on the vacuum: $T = 0\ ,\ \ \mu_B = 0$

- Obvious importance.

Remarks on $\mu_B \neq 0$

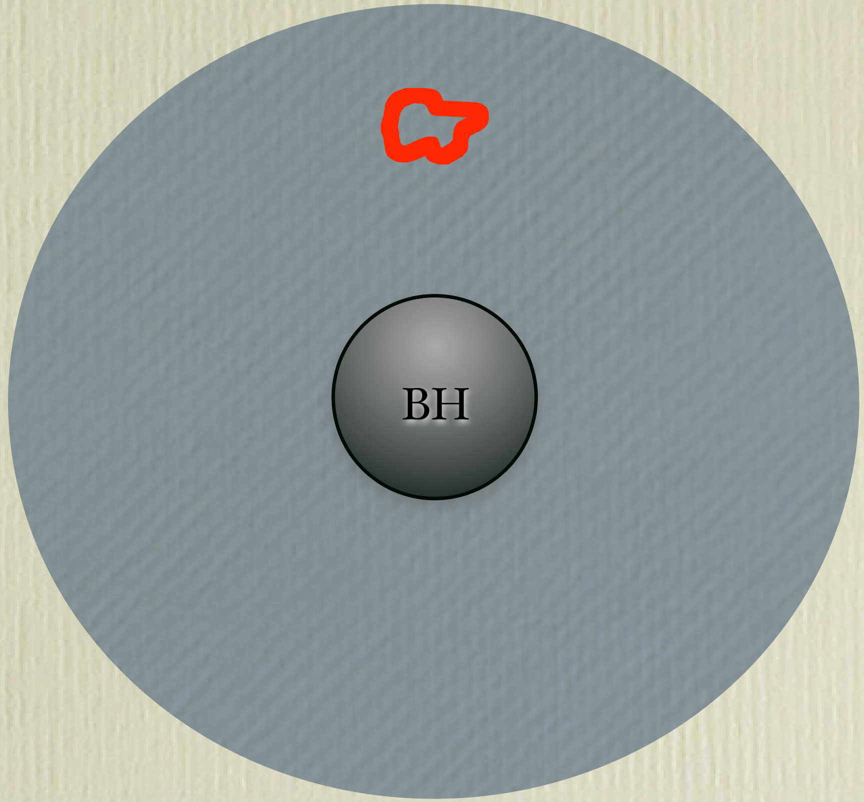
Concluding thoughts

The deconfined phase.



Exploit two universal properties

Deconfined plasma ⟷



Witten '98

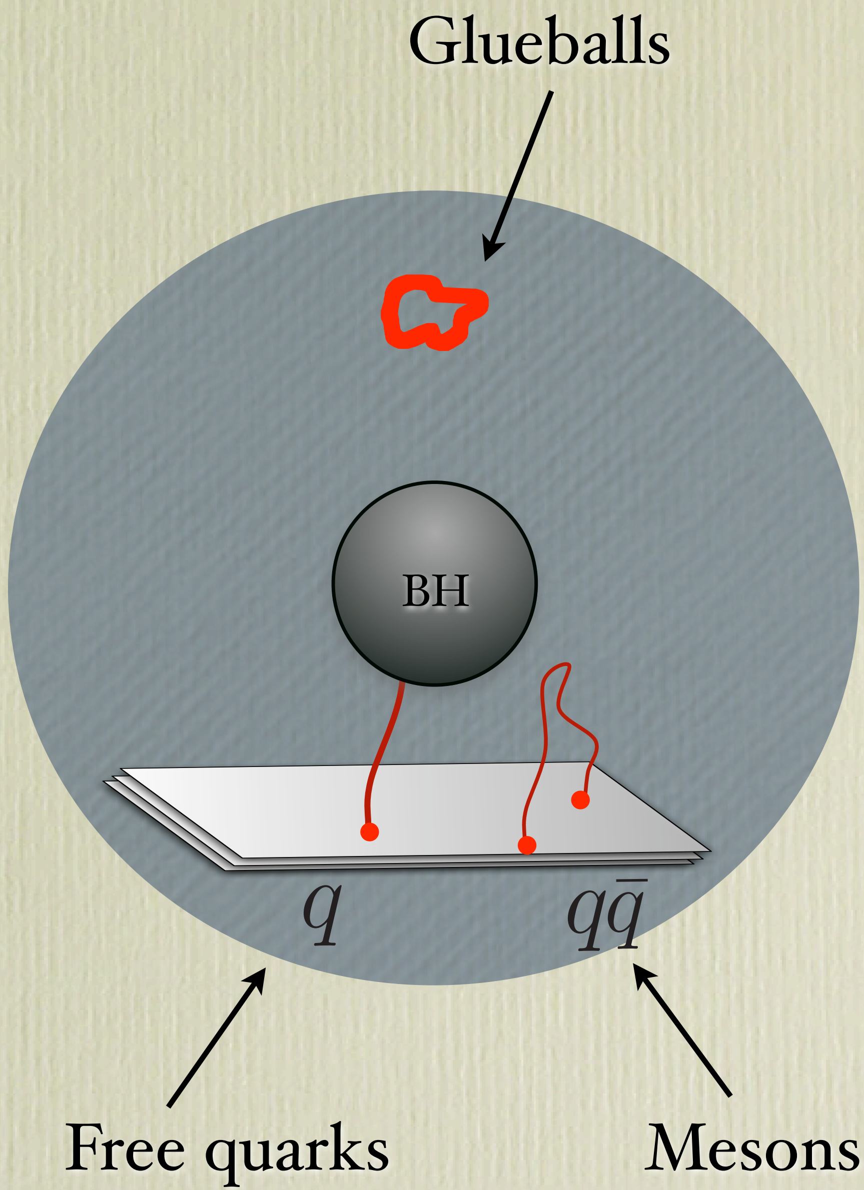
Universal ratio: $$\frac{\eta}{s} = \frac{1}{4\pi}$$

Policastro, Son & Starinets '01
Kovtun, Son & Starinets '03

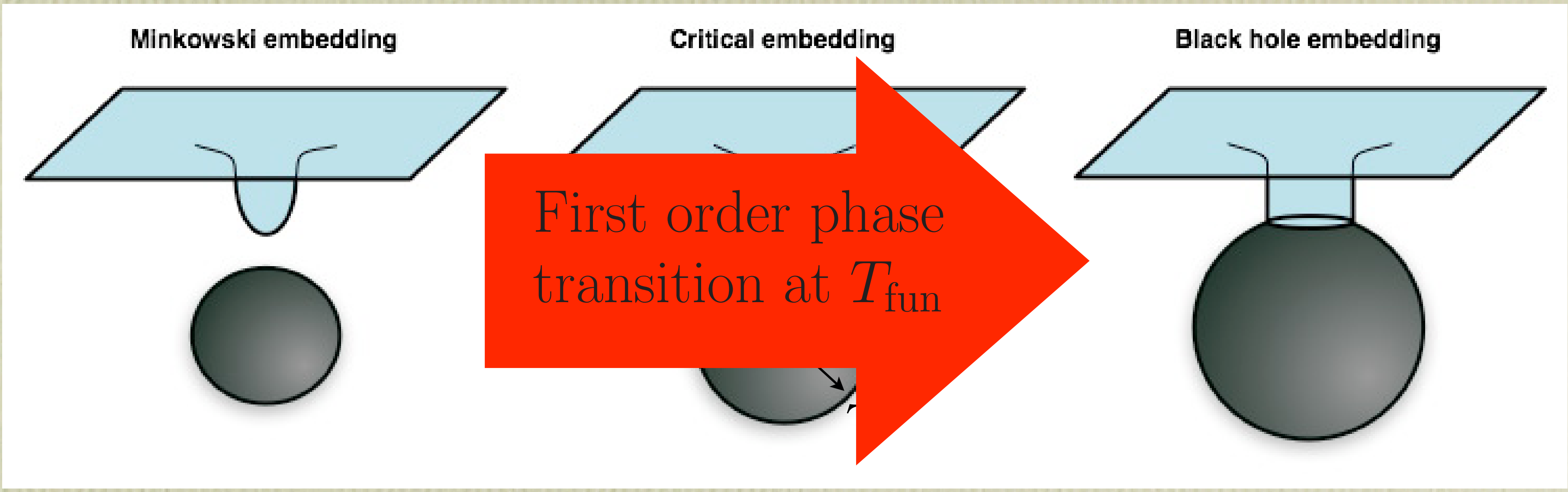
Exploit two universal properties

$N_f \ll N_c$ quark flavours ⟷

Karch & Randall ’01
Karch & Katz ‘02



Phase transitions for mesons

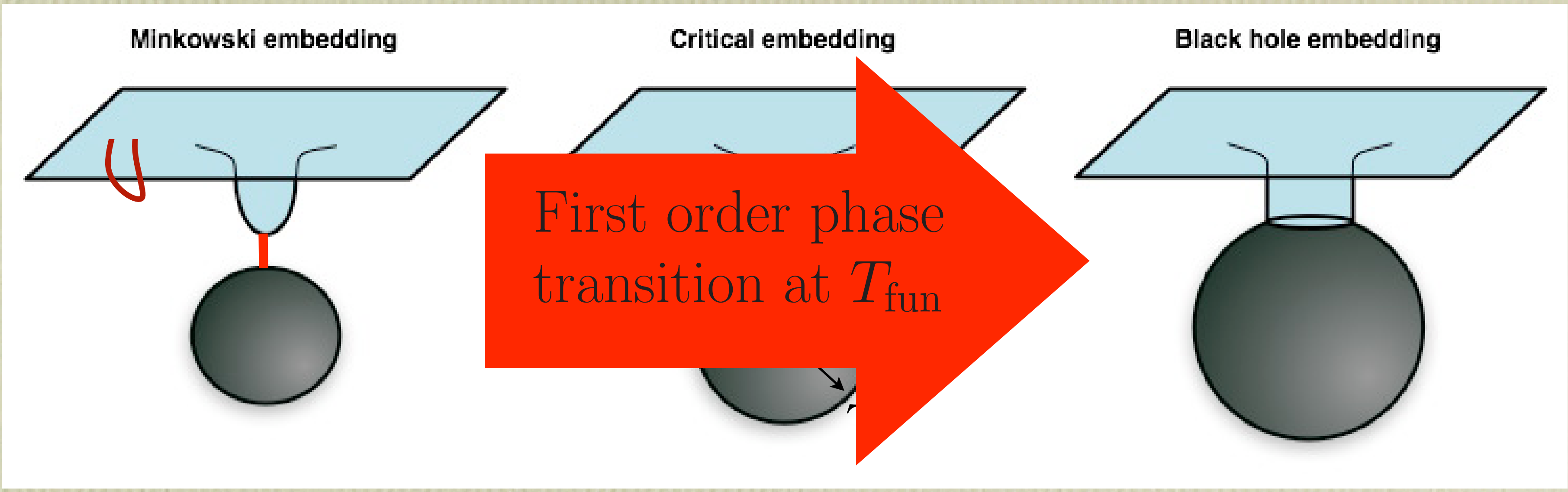


(Gluons are deconfined in both phases!)

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

D.M., Myers & Thomson '06

Phase transitions for mesons



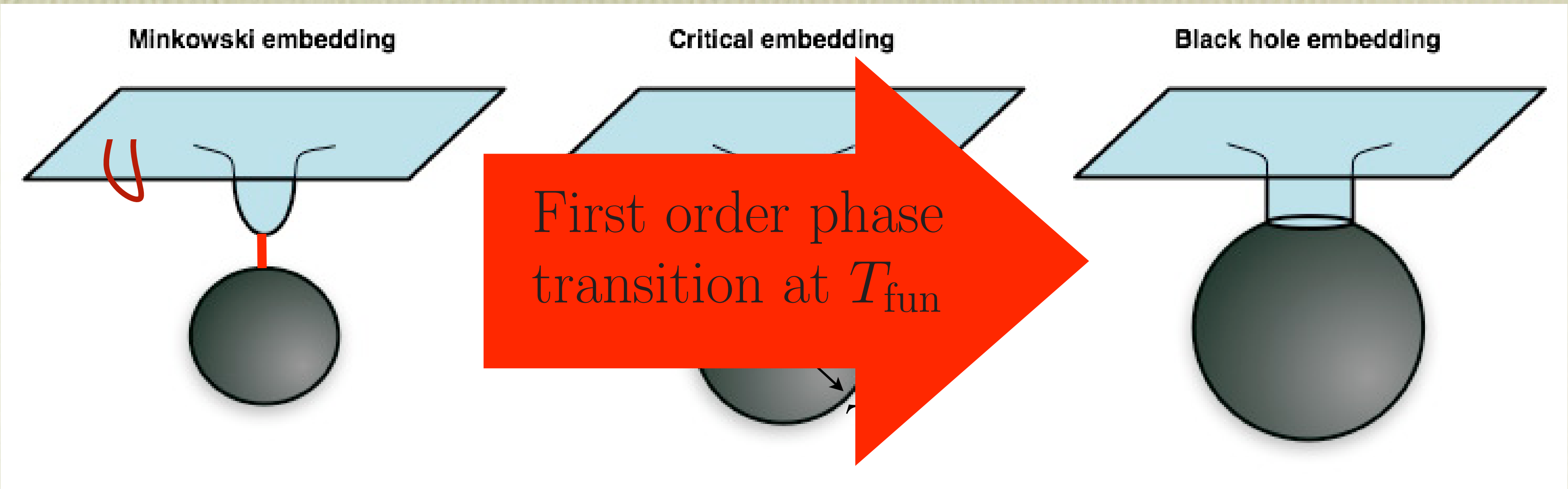
- Discrete set of mesons with mass gap:

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

- Massive quarks.

- Heavy mesons survive deconfinement!

Phase transitions for mesons



- No quasi-particle excitations!

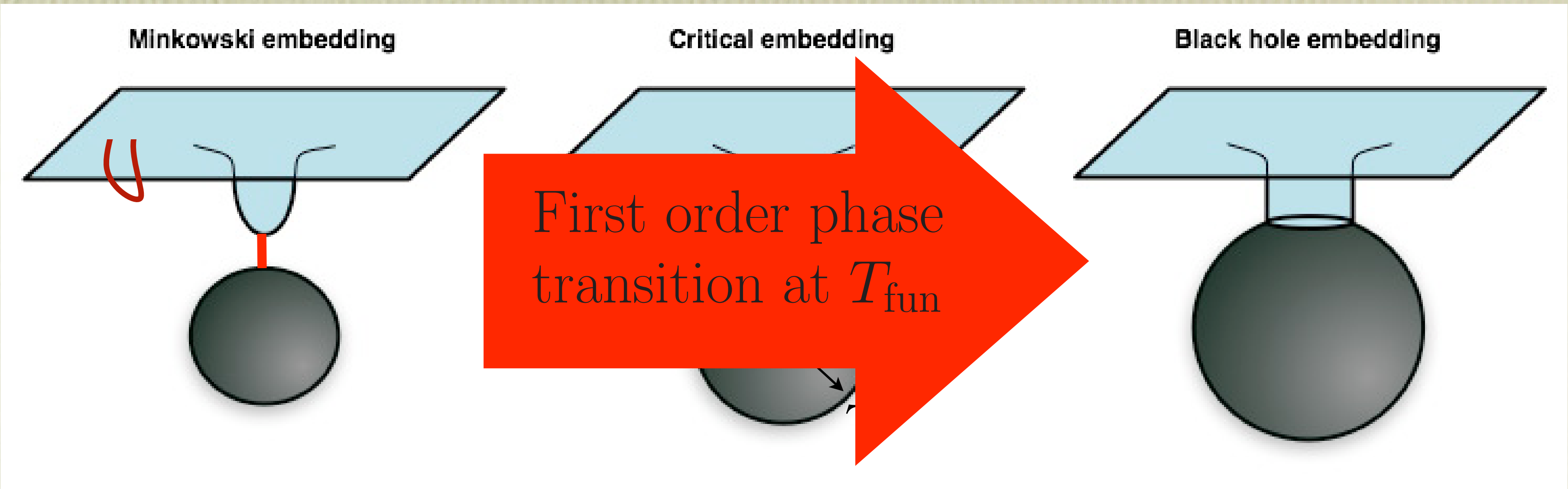
D.M., Myers & Thomson '06
Hoyos-Badajoz, Landsteiner & Montero '06

- Will illustrate this by computing a spectral function of electromagnetic currents, related to photon production:

$$\langle J_\mu^{\text{EM}} J_\mu^{\text{EM}} \rangle$$

D.M., Patiño-Jaidar '07

Phase transitions for mesons



- Heavy mesons survive deconfinement is in good agreement with lattice QCD, eg. for J/Ψ:

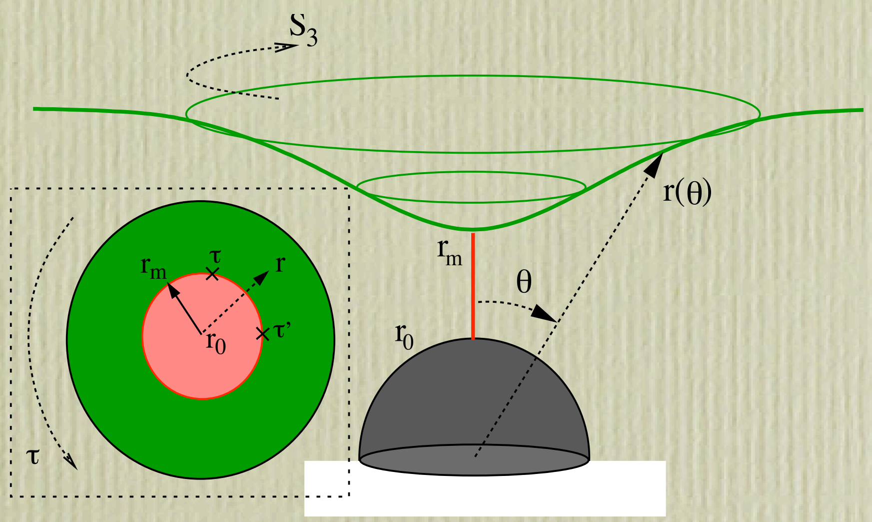
Lattice: $T_{\text{fun}} \simeq (317 - 403)$ MeV

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

Phase transitions for mesons

- Mesons absolutely stable at $N_c \to \infty$, $\lambda \to \infty$, but acquire widths away from this limit.

- Finite coupling: String worldsheet instantons. Faulkner & Liu '08



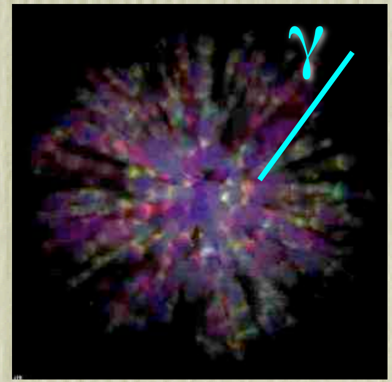
$$\Gamma \sim e^{-\sqrt{\lambda}} \sim e^{-M_q/T}$$

- Finite N: Hawking radiation.

$$\Gamma \sim 1/N_c^2$$

Spectral functions, quasiparticles and photon/dilepton production.

- Interesting because QGP is optically thin → Photons carry valuable information.



- Need to calculate: $N_\gamma \propto \eta^{\mu\nu}\chi_{\mu\nu}\,, \qquad \chi_{\mu\nu} \sim \mathrm{Im}\langle J^{\mathrm{EM}}_\mu J^{\mathrm{EM}}_\nu \rangle$

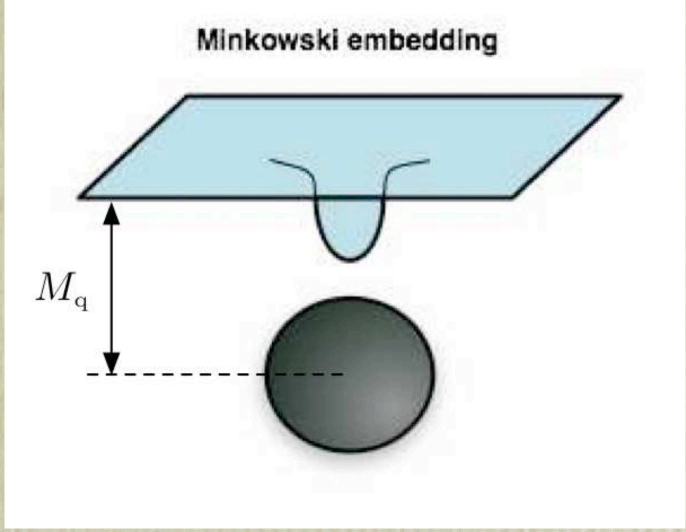
- Holographic results for massless matter:

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

Parnachev & Sahakian '06

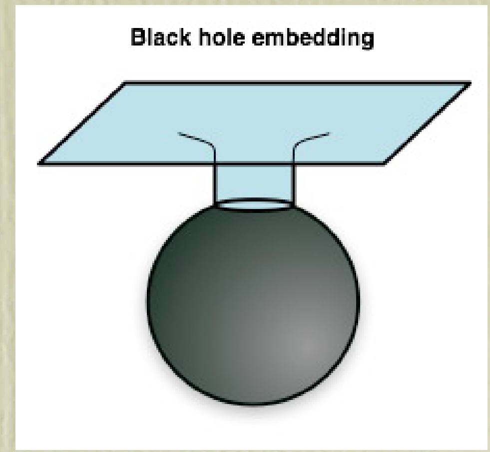
Spectral functions, quasiparticles and photon/dilepton production.

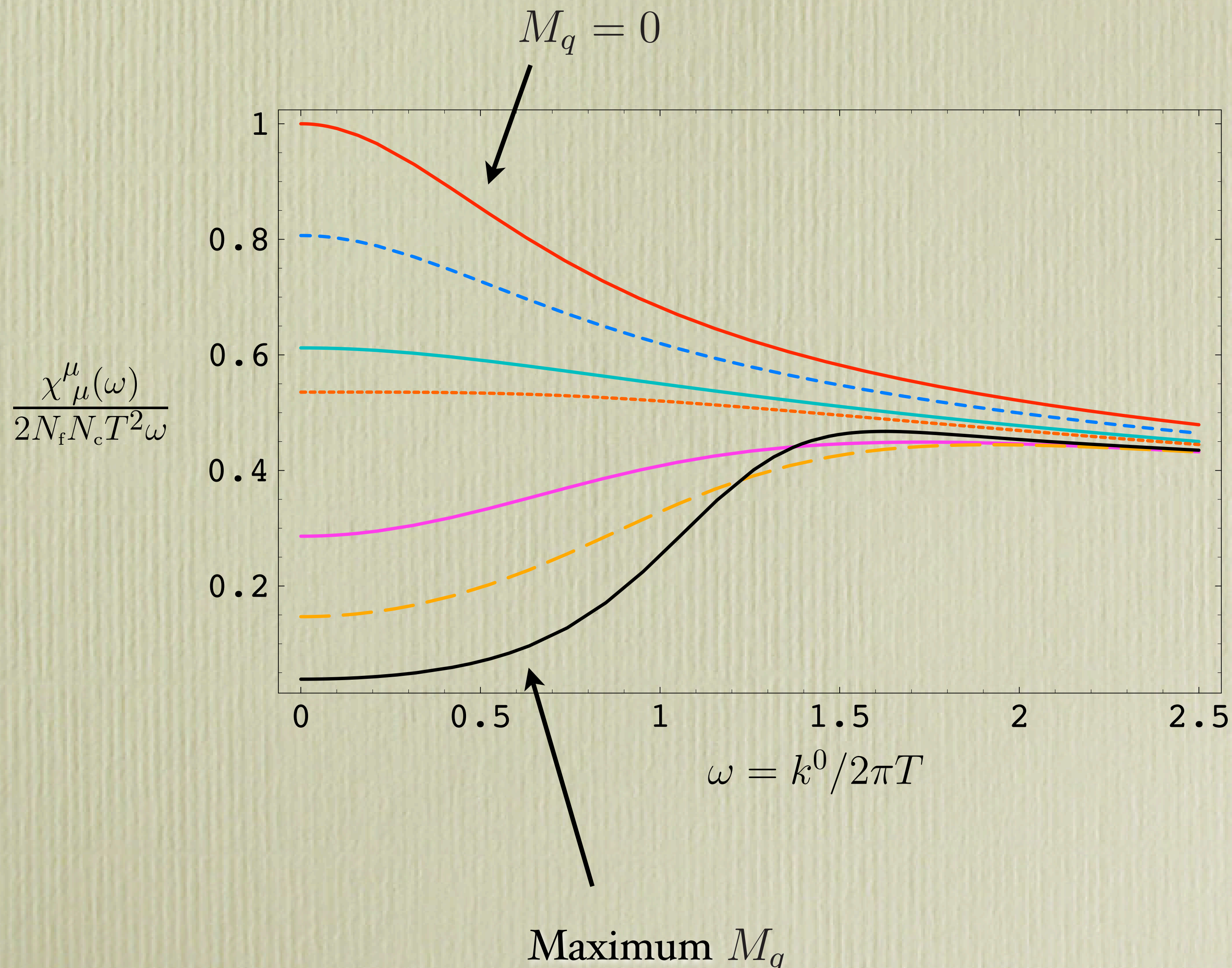
- Spectral function for Minkowski phase:



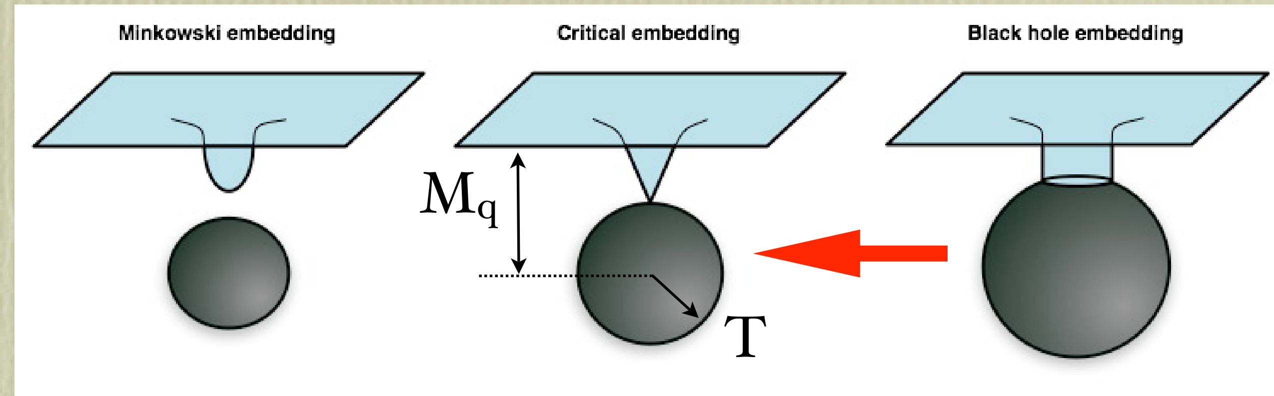
$$\chi = \sum \text{delta functions}$$

Spectral function for BH

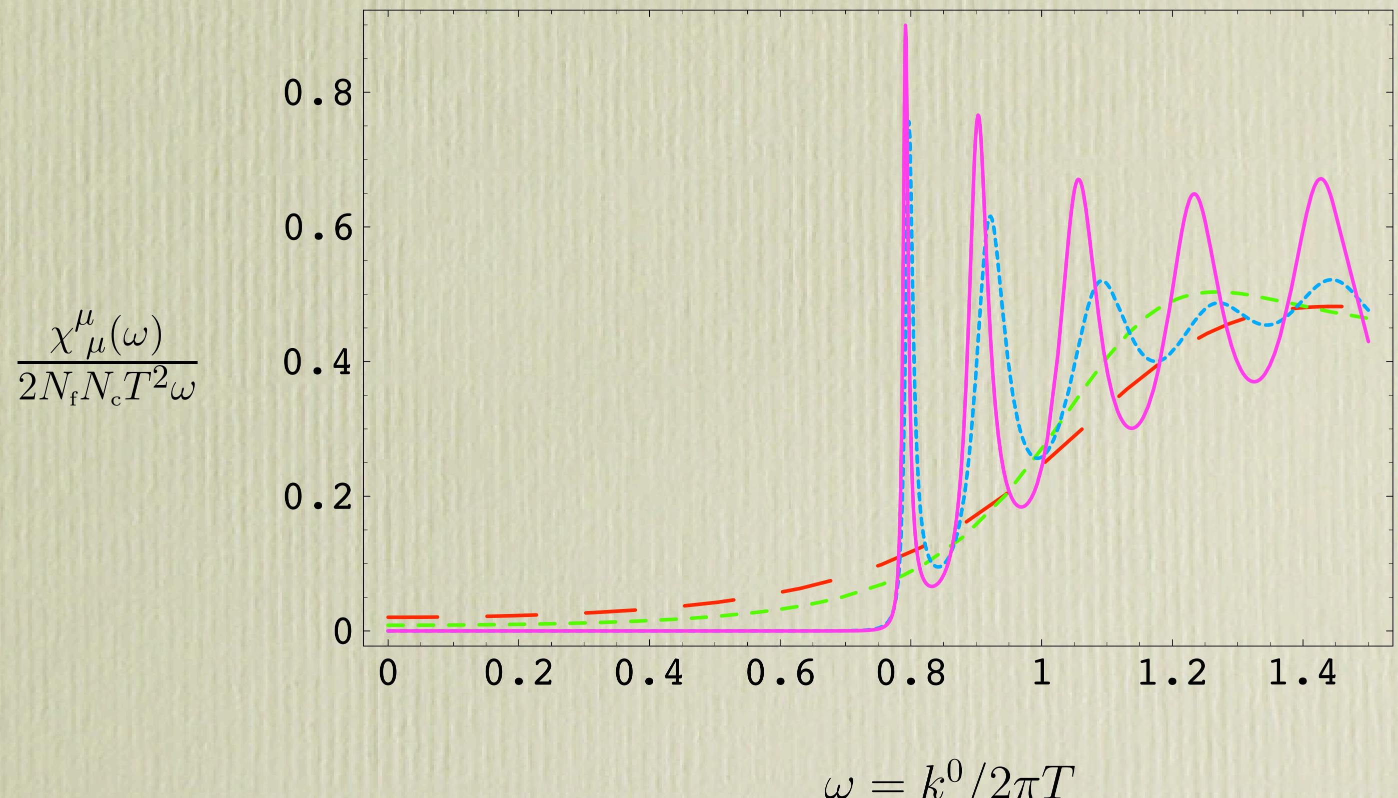




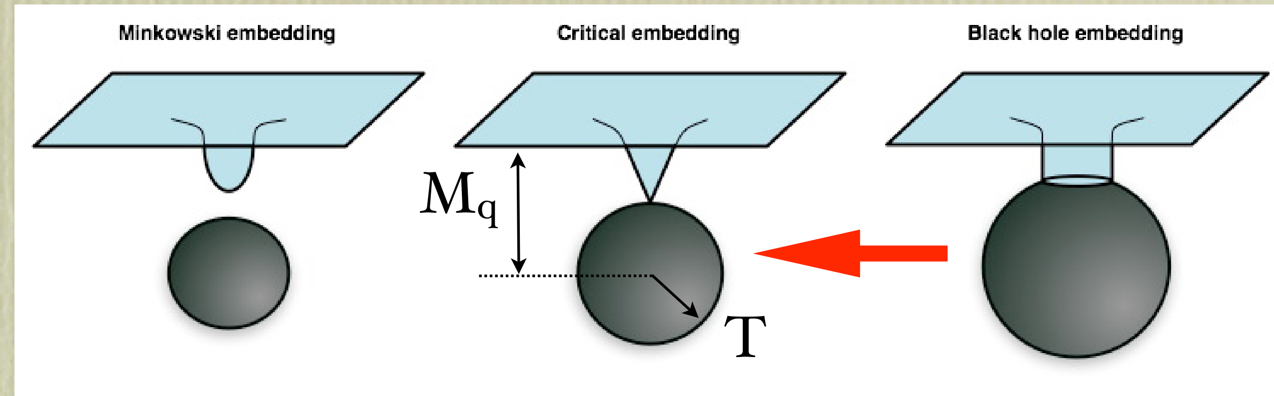
Approaching the critical embedding:



Peaks at null momentum!

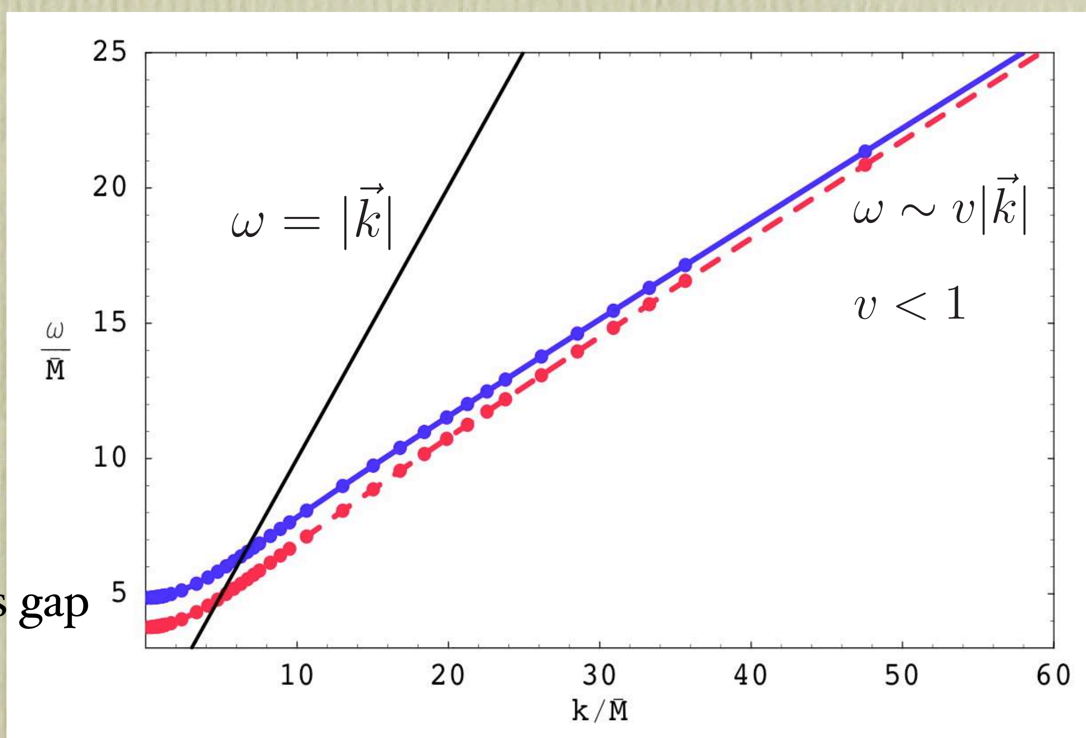


Approaching the critical embedding:



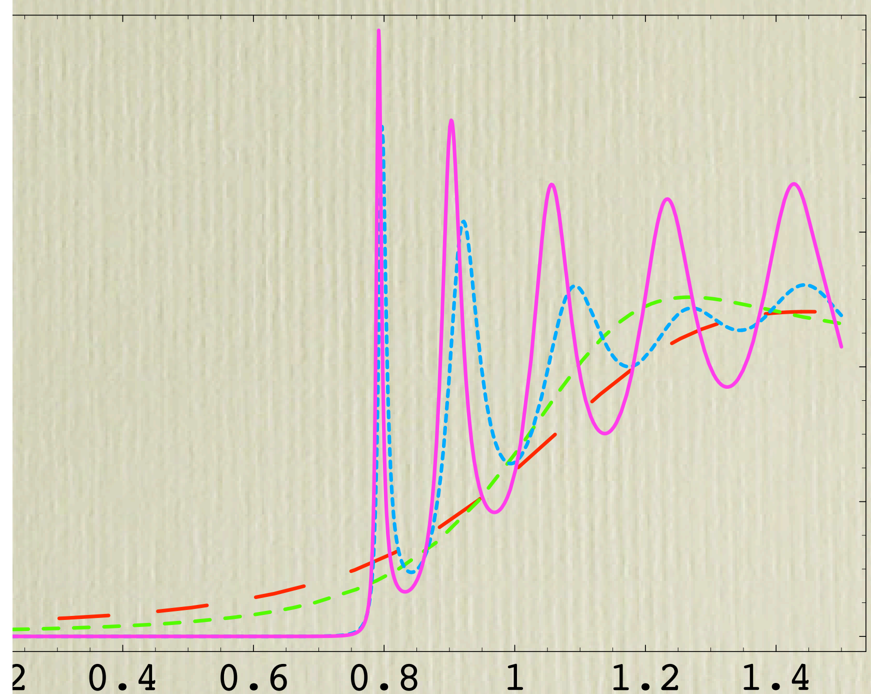
Dispersion relation for mesons

D.M., Myers & Thomson '07
Ejaz, Faulkner, Liu, Rajagopal & Wiedemann '07



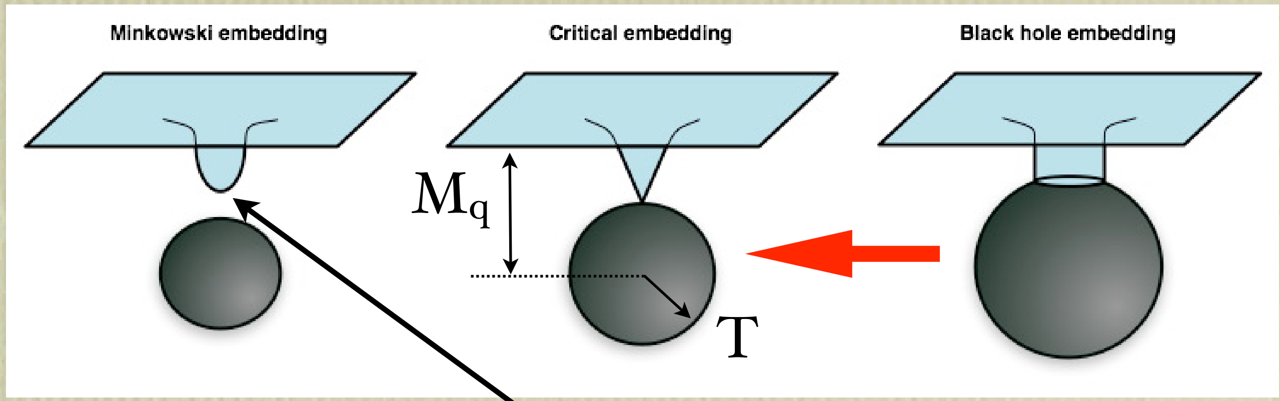
Mass gap

Peaks at null momentum!



$\omega = k^0/2\pi T$

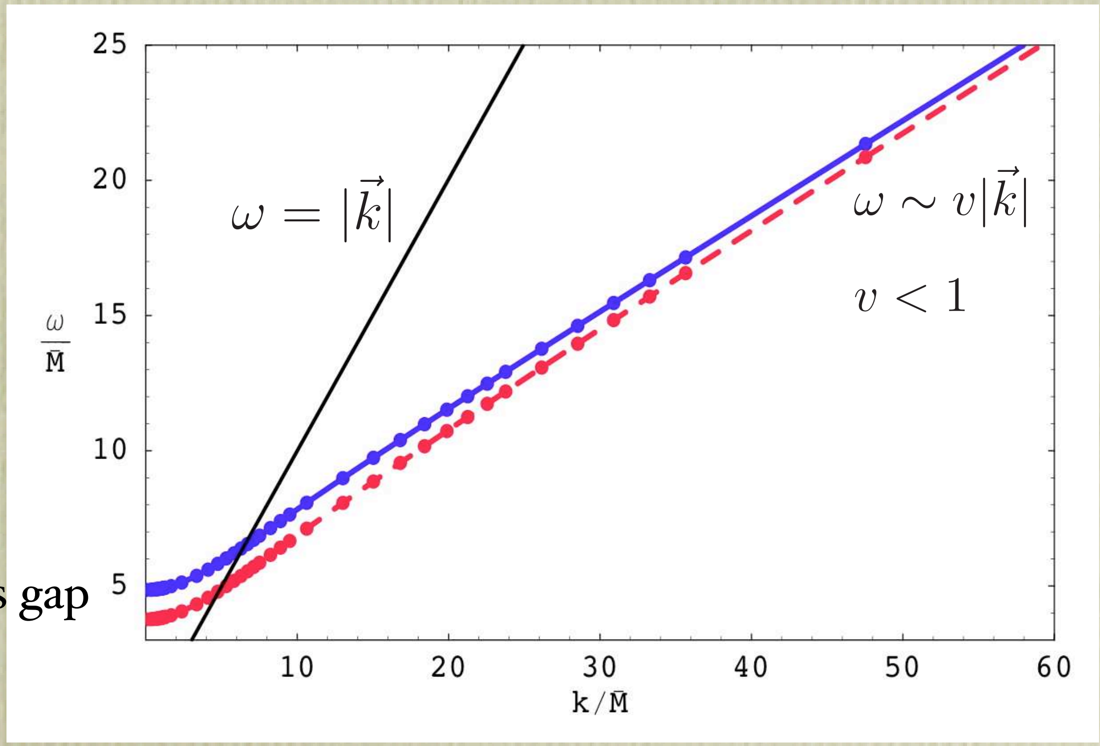
Approaching the critical embedding:



Limiting velocity
=
Local speed of light at the tip

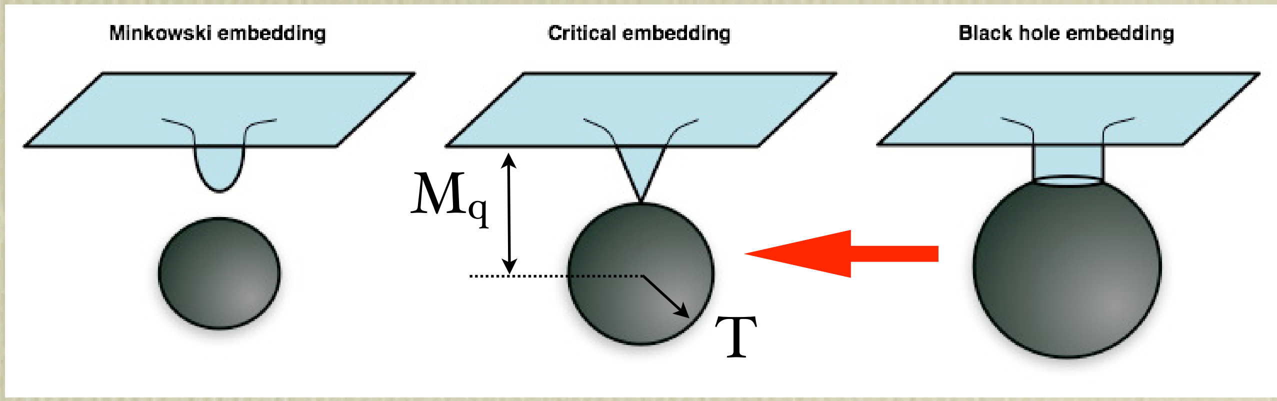
Dispersion relation for mesons

D.M., Myers & Thomson '07
Ejaz, Faulkner, Liu, Rajagopal & Wiedemann '07



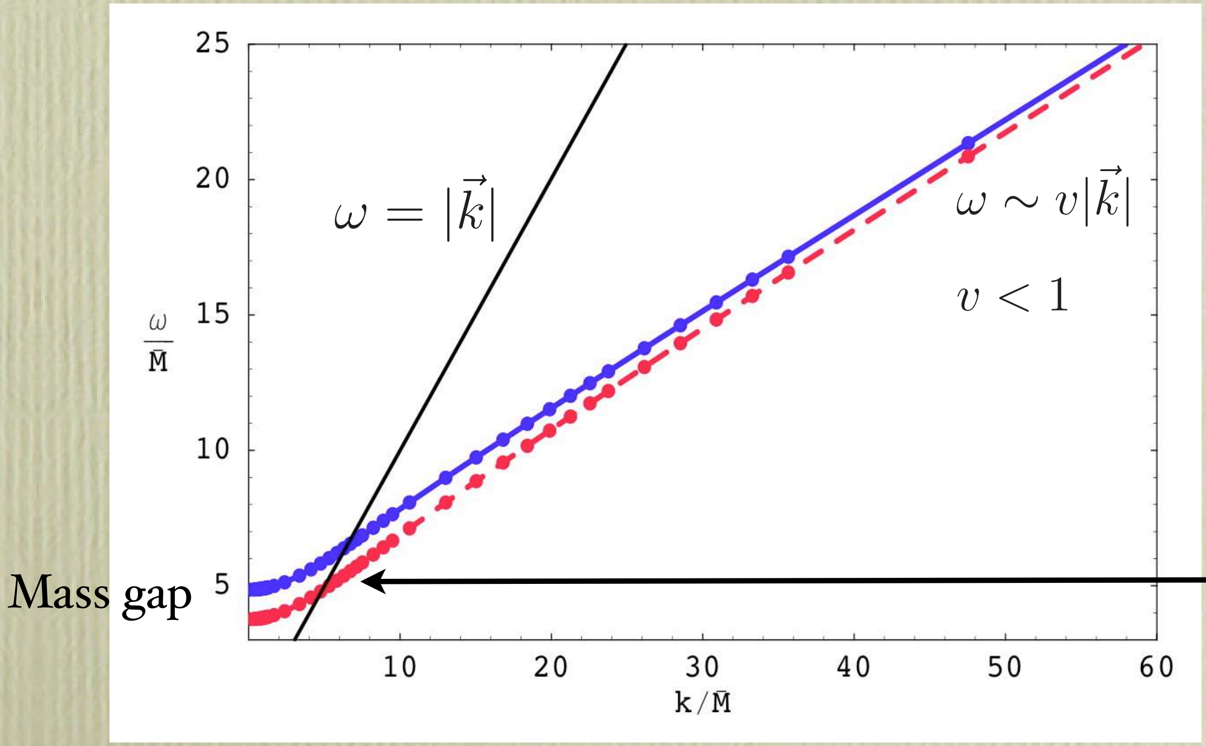
Mass gap

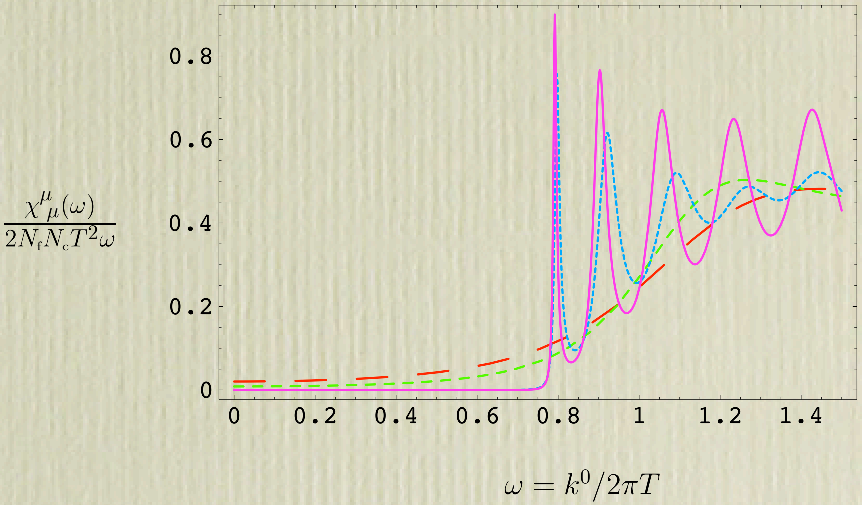
Approaching the critical embedding:



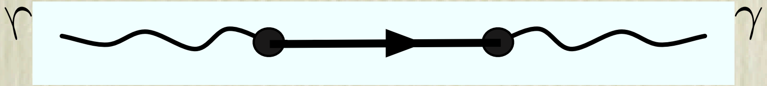
Dispersion relation for mesons

D.M., Myers & Thomson '07
Ejaz, Faulkner, Liu, Rajagopal & Wiedemann '07





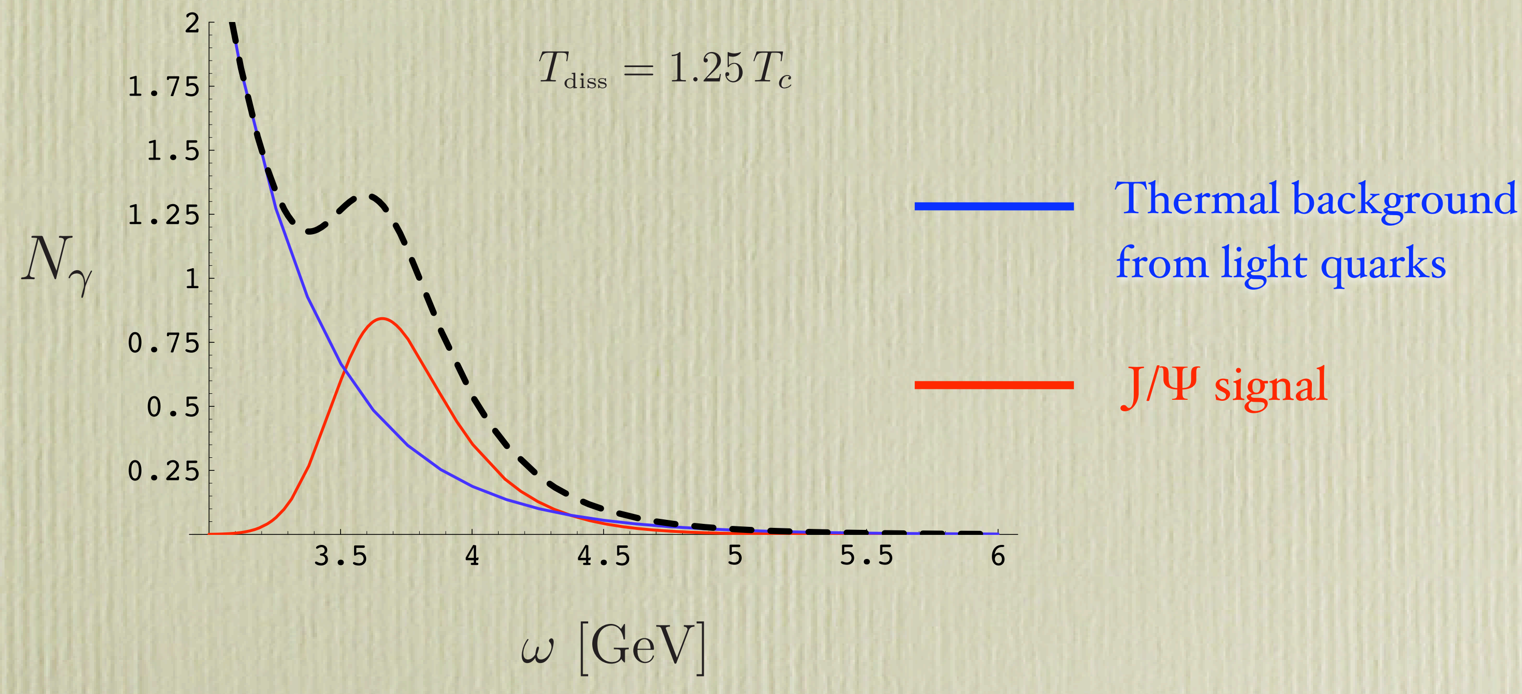
Meson with null momentum



Implications for HIC

Casalderey-Solana, D.M. '08

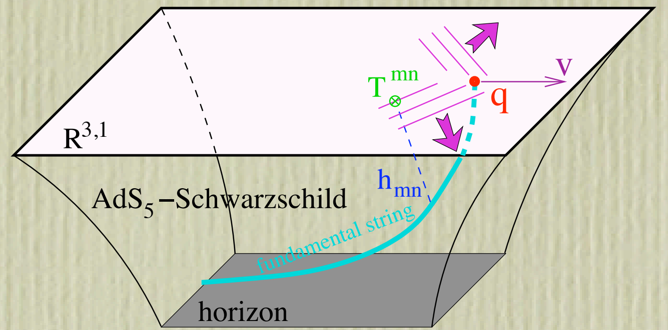
- Simple model yields, for LHC energies:



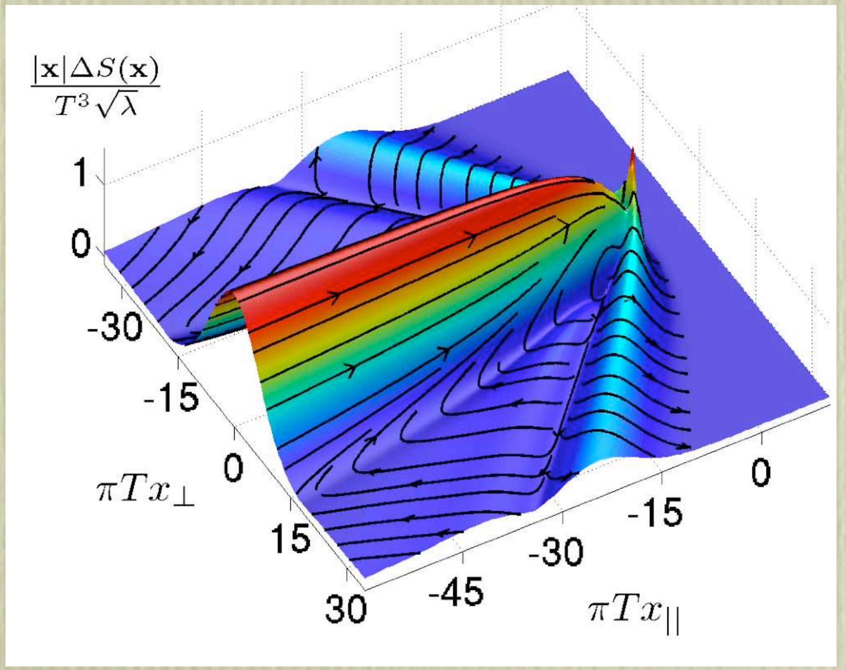
- Quadratically sensitive to $c\bar{c}$ cross-section

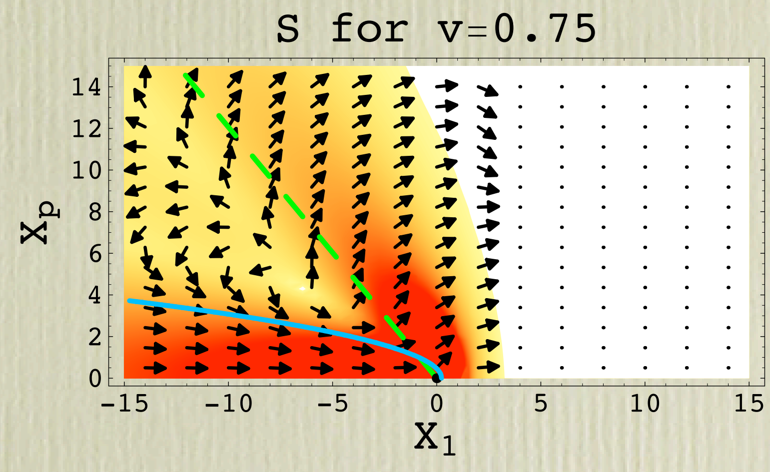
  -- not observable at RHIC.

Jet quenching/energy loss



Herzog, Karch, Kovtun, Kozcaz & Yaffe '06
Gubser '06
Liu, Rajagopal & Wiedemann '06

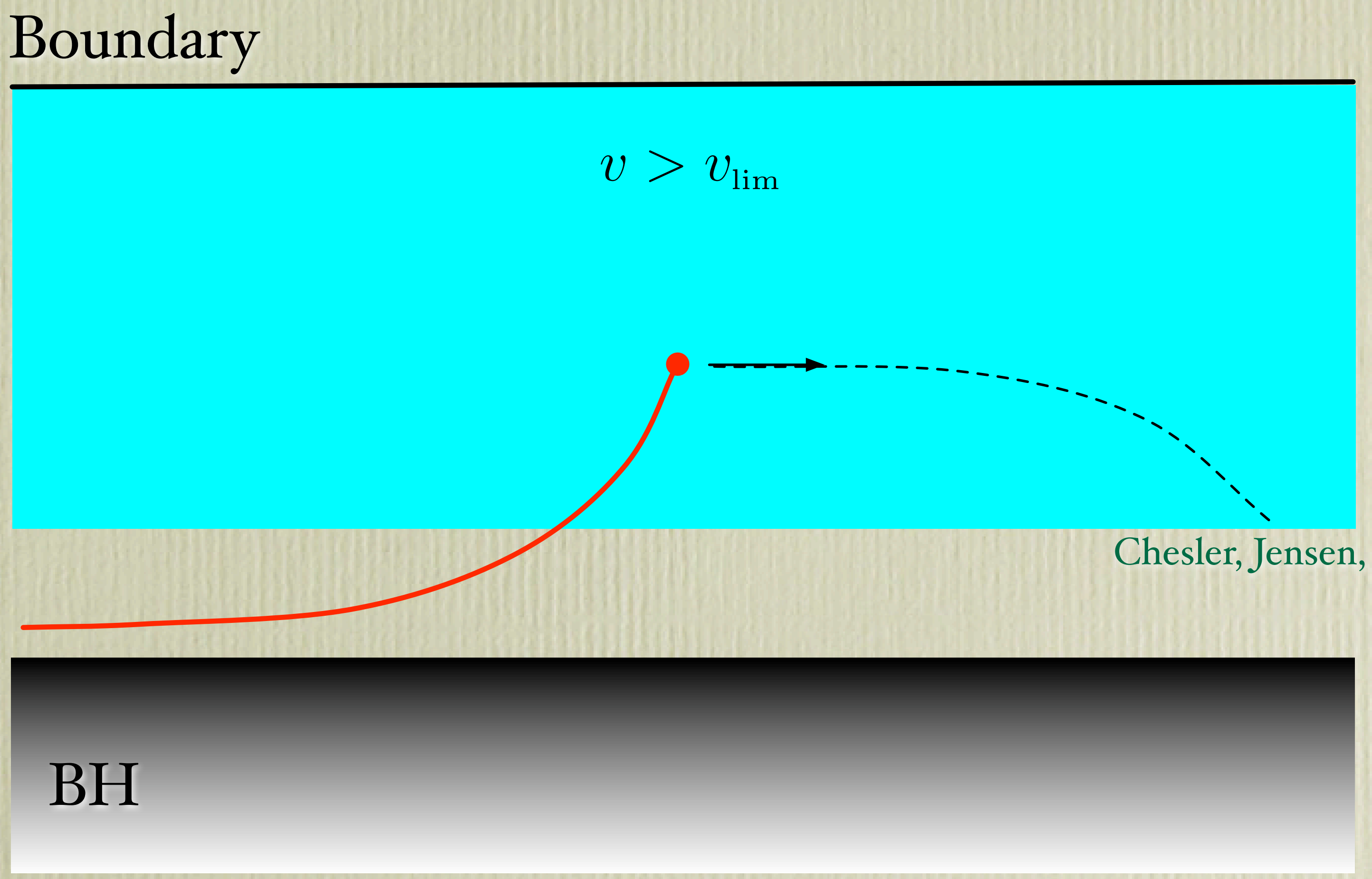




Friess, Gubser & Michalogiorgakis '06
Friess, Gubser, Michalogiorgakis & Pufu '06
Gubser & Pufu '07
Gubser, Pufu & Yarom '07
Yarom '07
Chessler & Yaffe '07

A new mechanism for quark energy loss

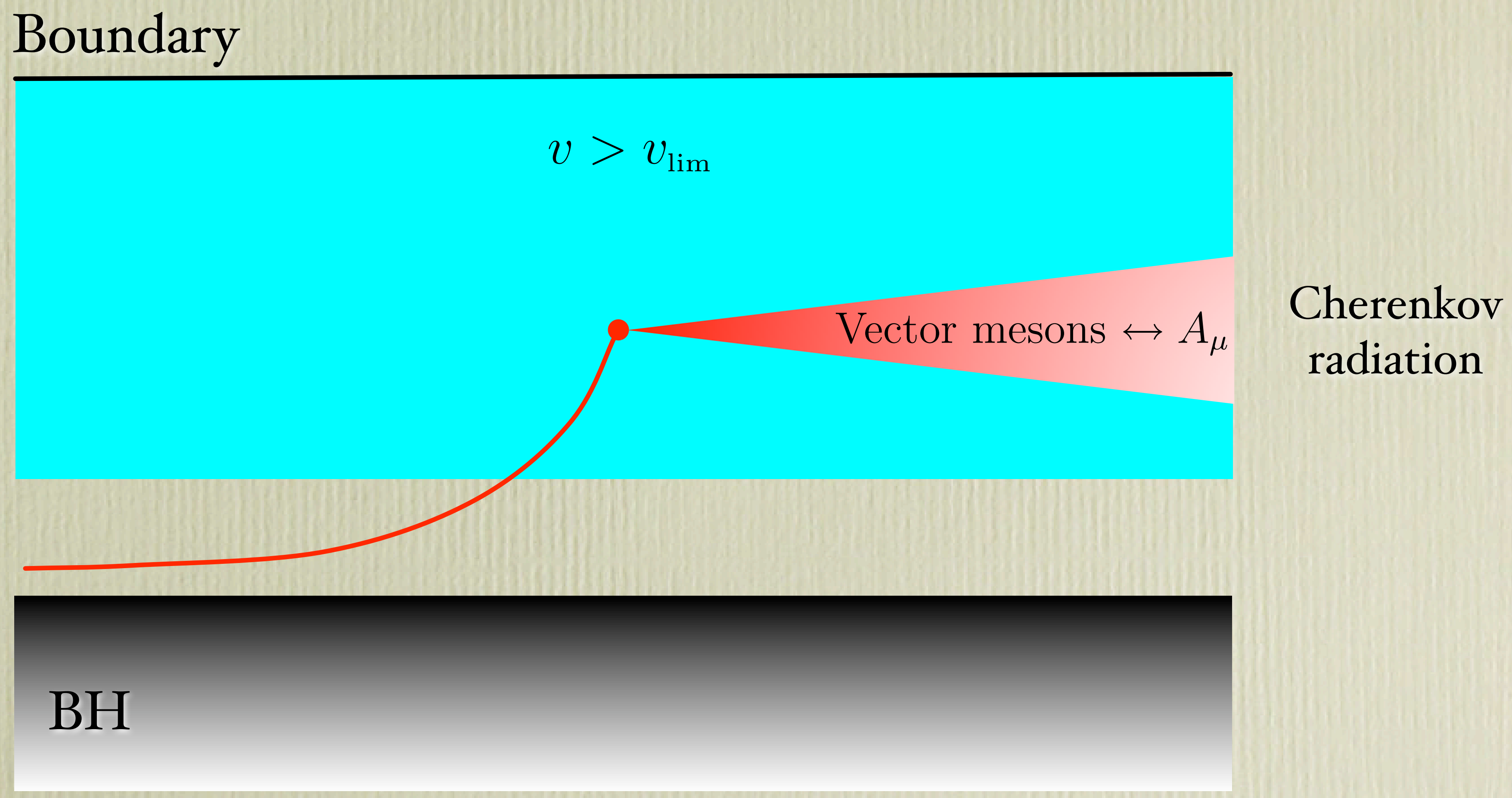
Casalderey-Solana, Fernandez & D.M. (to appear)



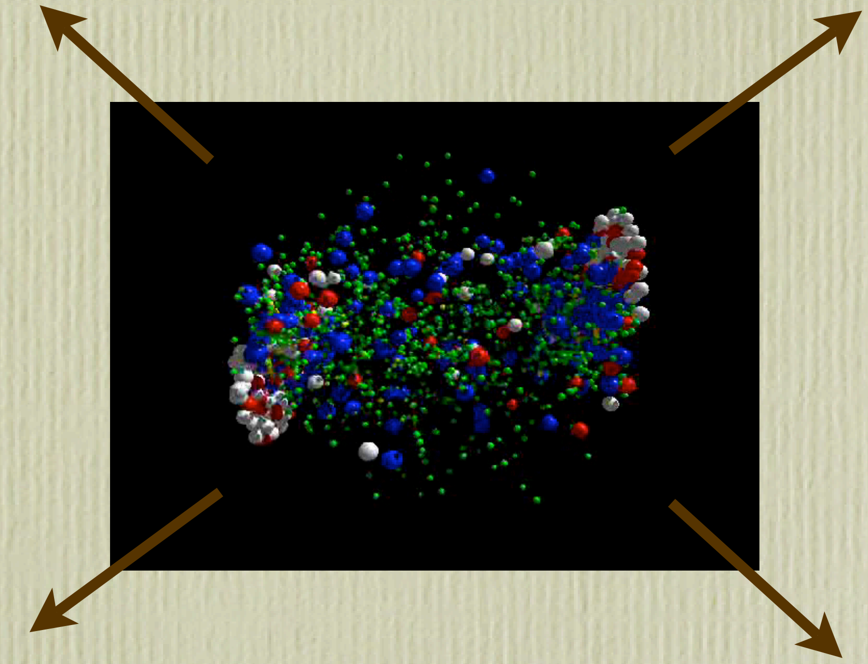
Chesler, Jensen, Karch & Yaffe '08

A new mechanism for quark energy loss

Casalderey-Solana, Fernandez & D.M. (to appear)



Expanding plasmas

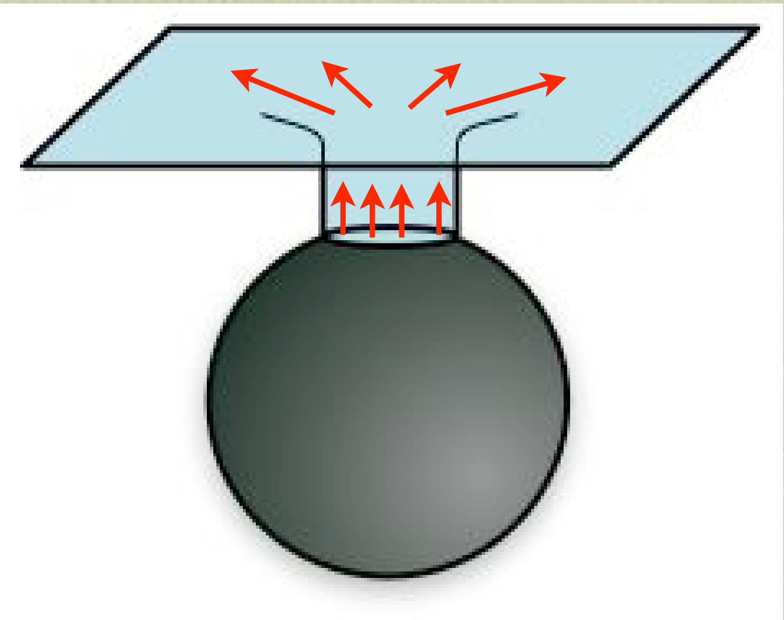


Janik & Peschanski '05
Janik & Peschanski '06
Kajantie & Tahkokallio '06
Janik '06
Sin, Nakamura & Kim '06
Nakamura & Sin '06
Friess, Gubser, Michalogiorgakis & Pufu '06
Heller & Janik '07
Benicasa, Buchel, Heller & Janik '07
Kovchegov & Taliotis '07
Bhattacharyya, Hubeny, Minwalla & Rangamani '07
Buchel '08
Buchel & Paulos '08
Heller, Surowka, Loganayagam, Spalinski & Vazquez '08
Kinoshita, Mukohyama, Nakamura & Oda '09
Figueras, Hubeny, Rangamani & Ross '09
Chesler & Yaffe '09
Beuf, Heller, Janik & Peschanski '09

- More work on meson dynamics needed.

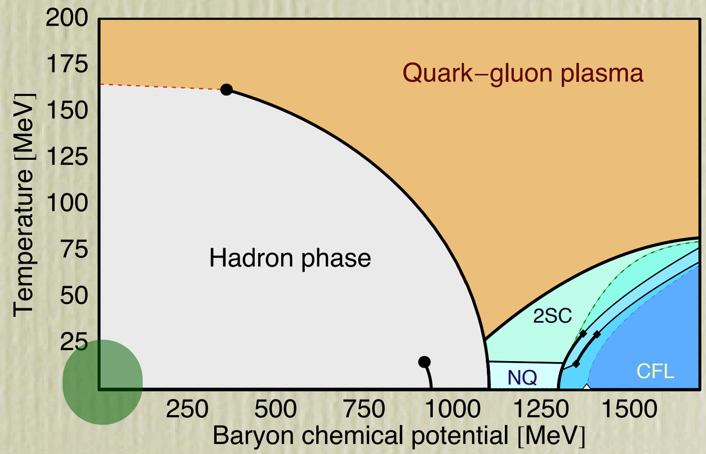
Grosse, Janik & Surówka '07

Mesons in external E&M fields



Filev, Johnson, Rashkov & Viswanathan ‘ 07
Erdmenger, Meyer & Shock ’07
Albash, Filev, Johnson & Kundu ’07
Karch & O’Bannon ‘07
Johnson & Kundu ’08
Jensen, Karch & Price ‘08
Bergman, Lifschytz & Lippert ’08
Rebhan, Schmitt & Stricker ’09
Filev, Johnson & Shock ’09
Johnson & Kundu ‘09

The vacuum.

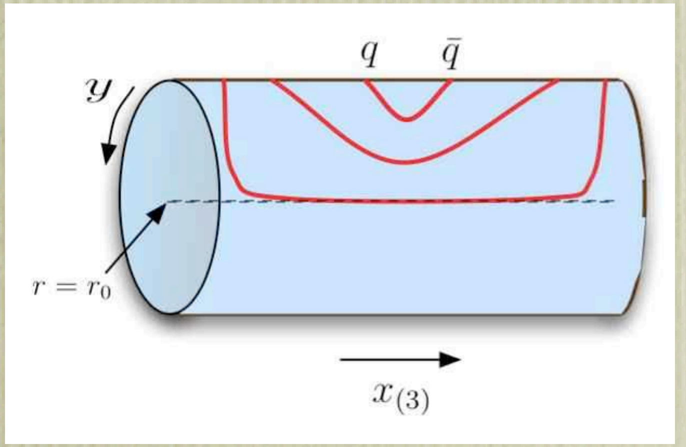


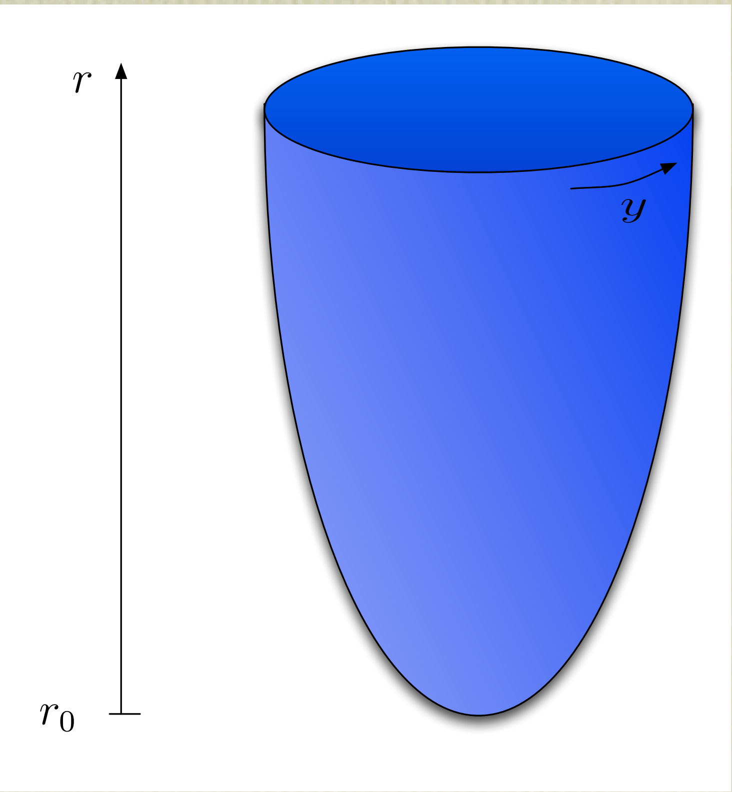
Quark–gluon plasma
Hadron phase
2SC
NQ
CFL
Temperature [MeV]
200
175
150
125
100
75
50
25
250
500
750
1000
1250
1500
Baryon chemical potential [MeV]

Two fundamental properties:
I. Confinement

- Simplest model:
  D4-branes on a circle.

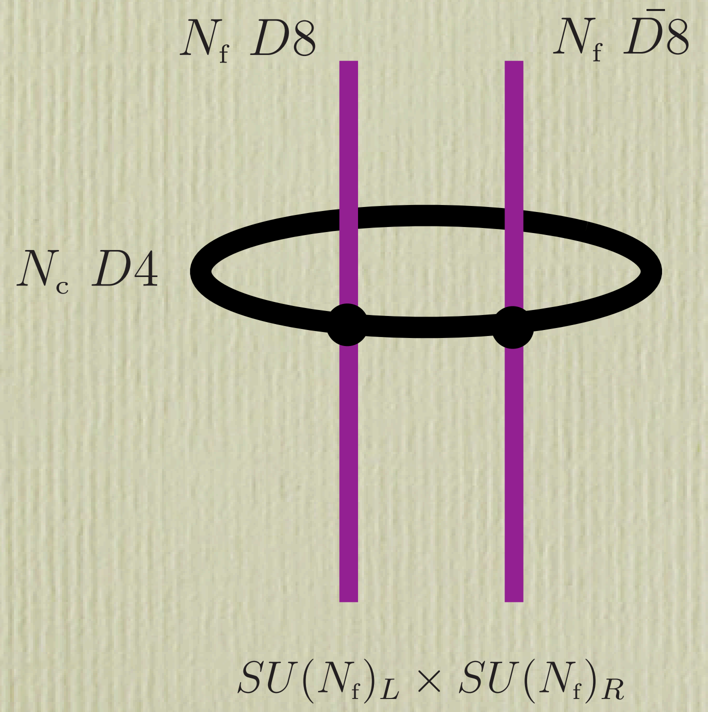
Witten '98





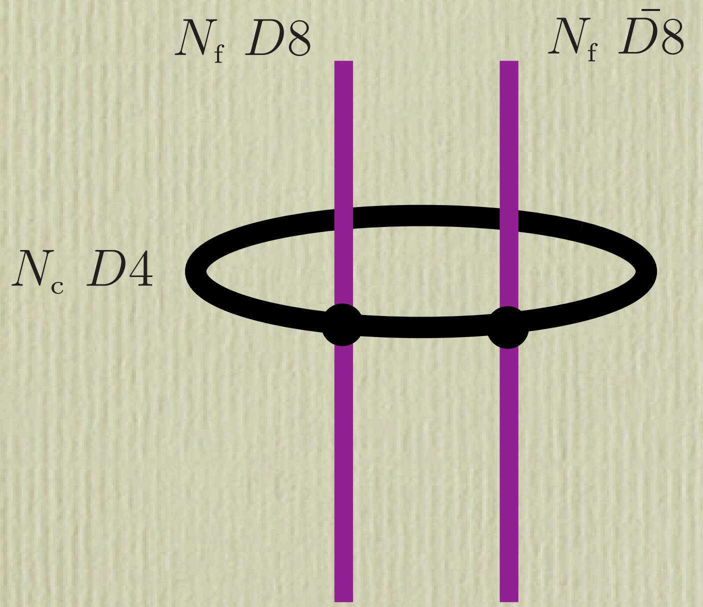
Two fundamental properties: II. Non-Abelian SχSB

Sakai & Sugimoto '04

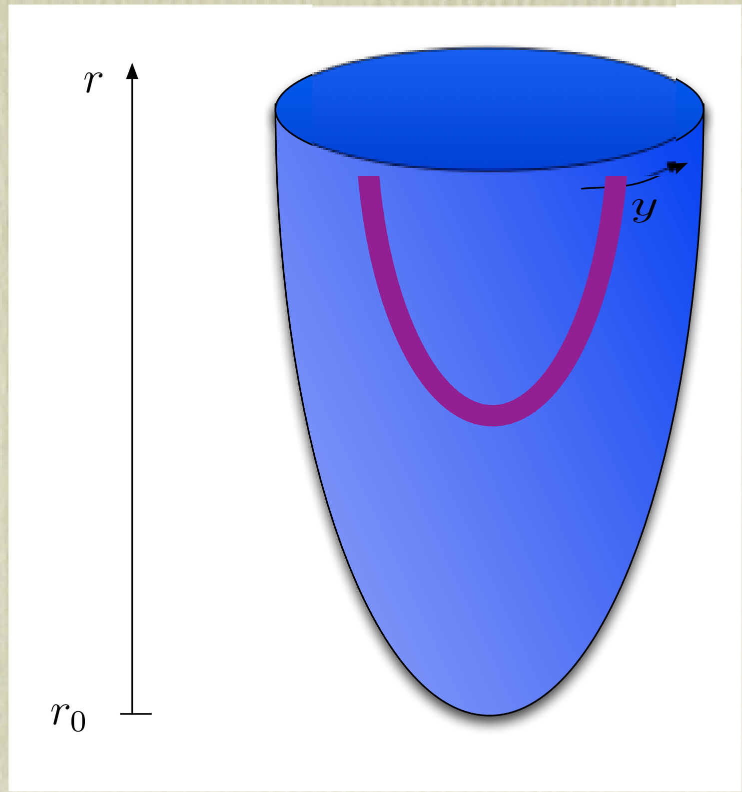


Two fundamental properties: II. Non-Abelian SχSB

Sakai & Sugimoto '04



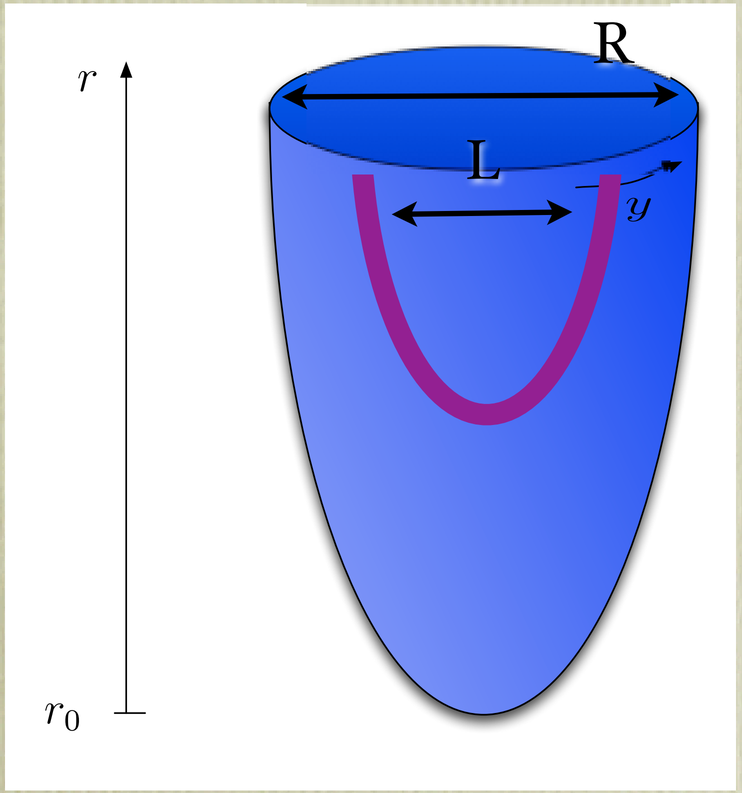
$SU(N_f)_L \times SU(N_f)_R$



$SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_V$

Comments

- Check: Spectrum contains $N_f^2 - 1$ massless pions.
- Allows separation of confinement and chiral symmetry scales:



$$\Lambda_{\text{QCD}} \sim M_{\text{glueball}} \sim M_{\text{KK}} \sim 1/R$$

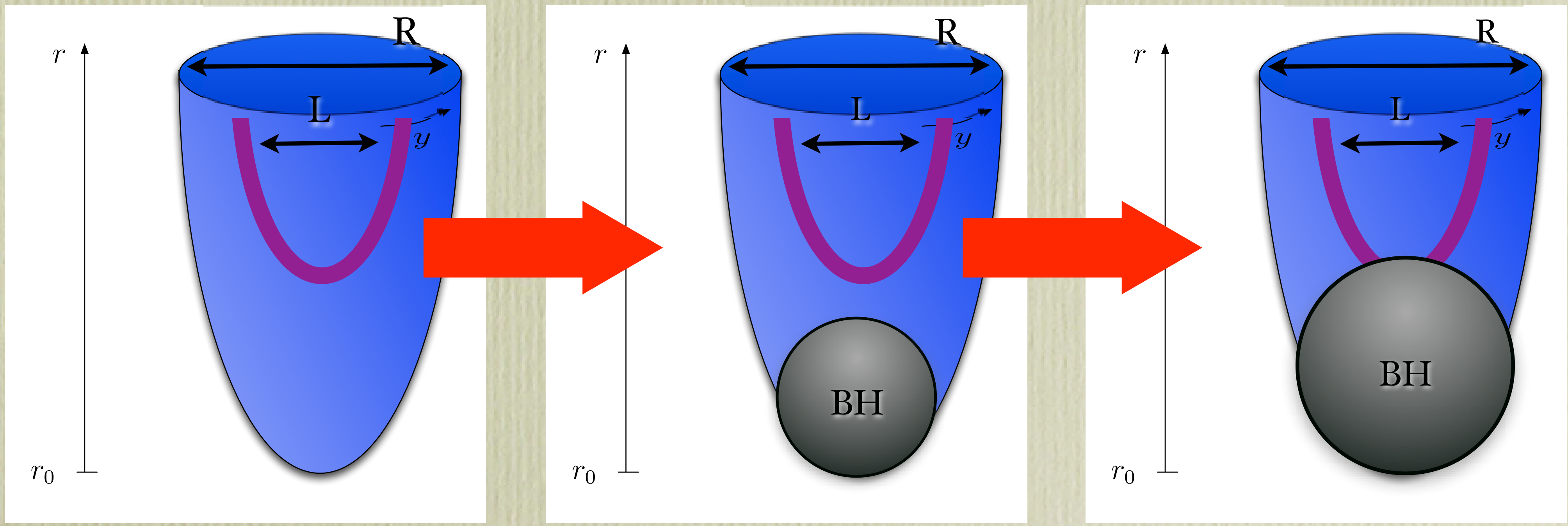
$$\langle \bar{\psi}\psi \rangle \sim M_{\text{meson}} \sim 1/L$$

Comments

- Can be seen by turning on temperature:

Aharony, Sonnenschein & Yankielowicz '06

Parnachev & Sahakyan '06



Deconfinement at T_c

Chiral symmetry restoration at $T_{\rm fun}$

Comments

- "Verified" on the lattice:

Separating the scales of confinement and chiral-symmetry breaking in lattice QCD with fundamental quarks

D. K. Sinclair

HEP Division and Joint Theory Institute, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439, USA

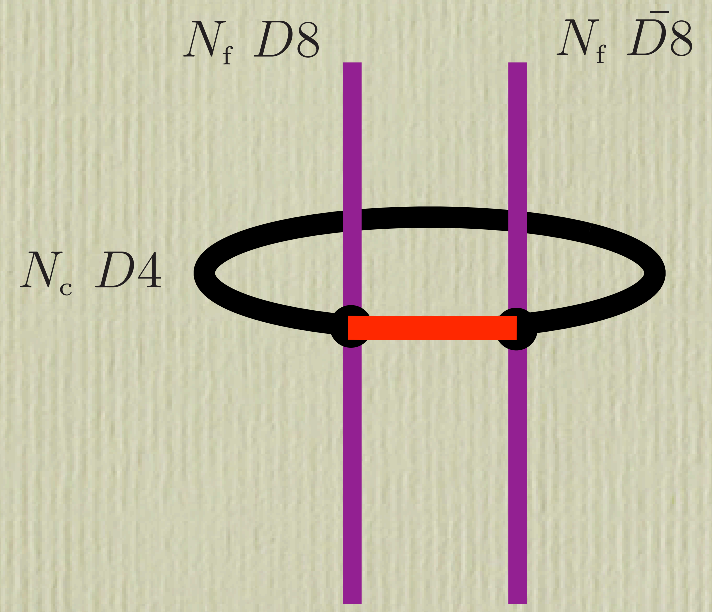
Abstract

Suggested holographic duals of QCD, based on AdS/CFT duality, predict that one should be able to vary the scales of colour confinement and chiral-symmetry breaking independently. Furthermore they suggest that such independent variation of scales can be achieved by the inclusion of extra 4-fermion interactions in QCD. We simulate lattice QCD with such extra 4-fermion terms at finite temperatures and show that for strong enough 4-fermion couplings the deconfinement transition occurs at a lower temperature than the chiral-symmetry restoration transition. Moreover the separation of these transitions depends on the size of the 4-fermion coupling, confirming the predictions from the proposed holographic dual of QCD.

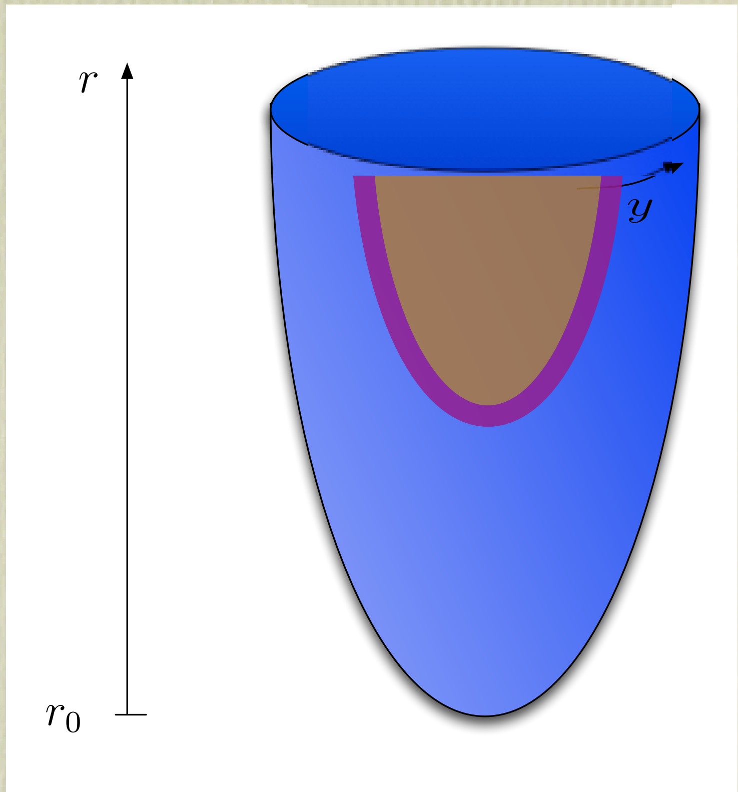
Comments

- Quark masses require non-local operators:

Aharony & Kutasov '08
McNees, Myers & Sinha '08



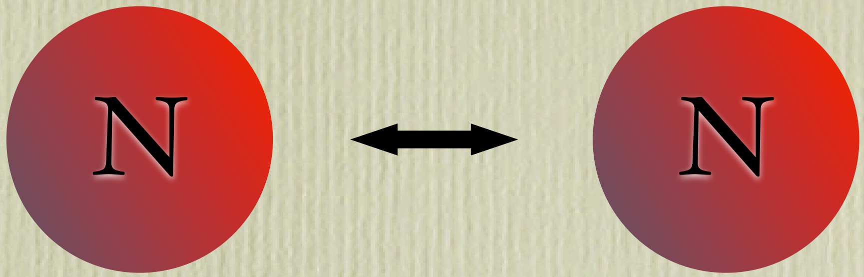
$$\mathcal{O} \sim \psi_L^\dagger \, P \, e^{i\int A} \, \psi_R$$



- Alternatively: Tachyon condensation.

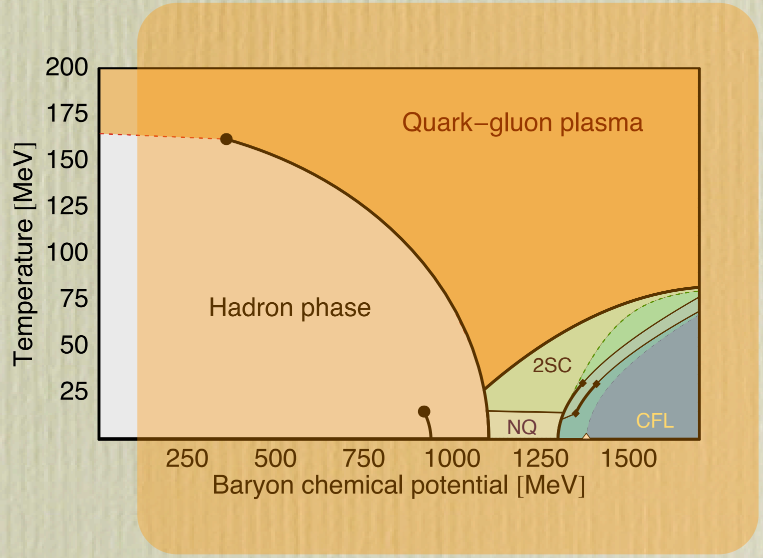
Casero, Kiritsis & Paredes '07
Bergman, Seki & Sonnenschein '07
Dhar & Nag '07
Dhar & Nag '08

Recent application: N-N force



Kim & Zahed '09
Hashimoto, Sakai & Sugimoto '09
Kim, Lee & Yi '09

Remarks on finite chemical potential.



General remarks

- The good:
  - Very hard on the lattice.
  - Very easy in the string description.

- The bad:
  - Most models have scalars (eg. D3/D7)

Nakamura, Seo, Sin & Yogendran '06
Kobayashi, D.M., Matsuura, Myers & Thomson '06
Karch & O' Bannon '07

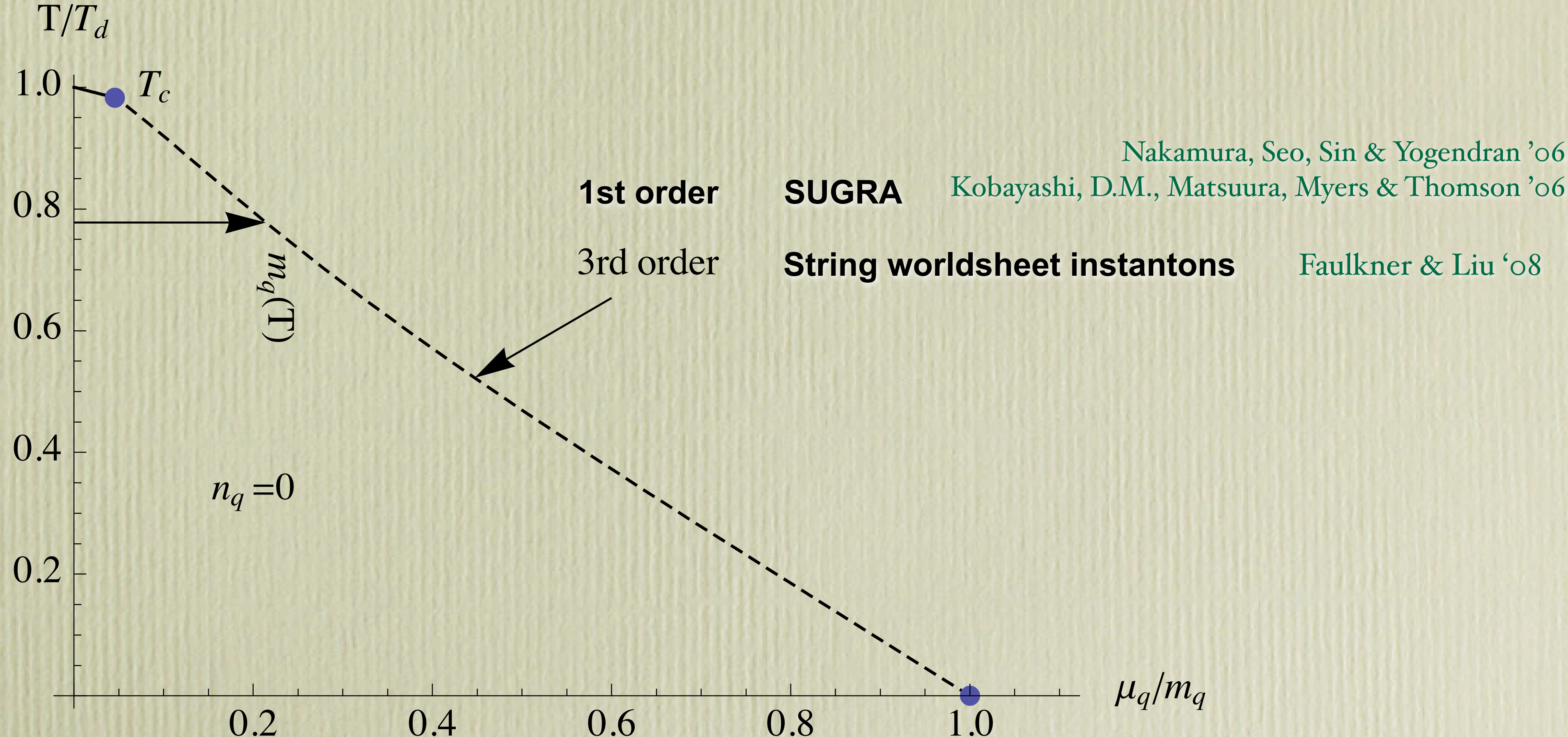
  - Fortunately, S&S does not.

Kim, Sin & Zahed '06
Horigome &Tanii '06
Sin '07
Yamada '07
Bergman, Lifschytz & Lippert '07

  - Very easy only at large N_c, where phase diagram is very different !

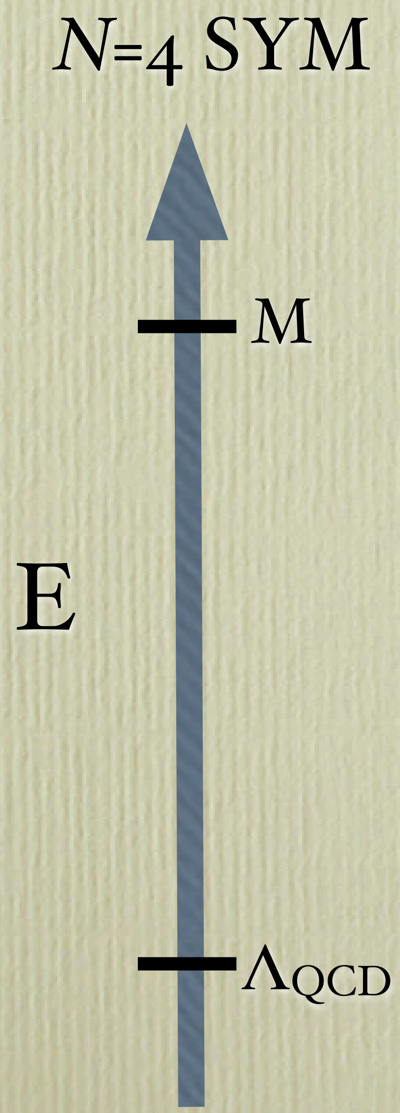
  - However, see CFL phase in Chen, Hashimoto & Matsuura (to appear)

Cautionary word about (ignoring) stringy effects



Concluding thoughts

Is SUGRA good or bad?



Corrections are $\mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{M}\right)$.

Within SUGRA approximation this is $\sim \mathcal{O}(1)$.

Pessimist: *"This is a disaster!"*.

Optimist: *"This gets the order of magnitude right!"*.

Eg.: Is $\frac{\eta}{s} = \frac{1}{4\pi}$ the biggest success or a disaster?

Thank you.