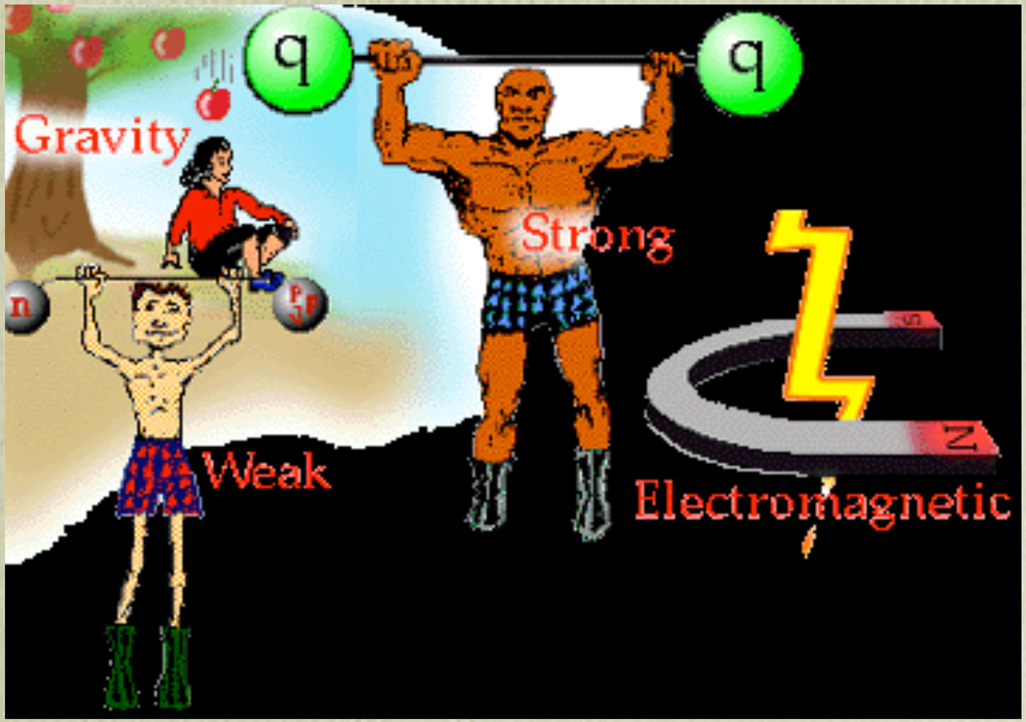
Quarks, Gluons and Black Holes

David Mateos
ICREA & University of Barcelona

Quantum ChromoDynamics...



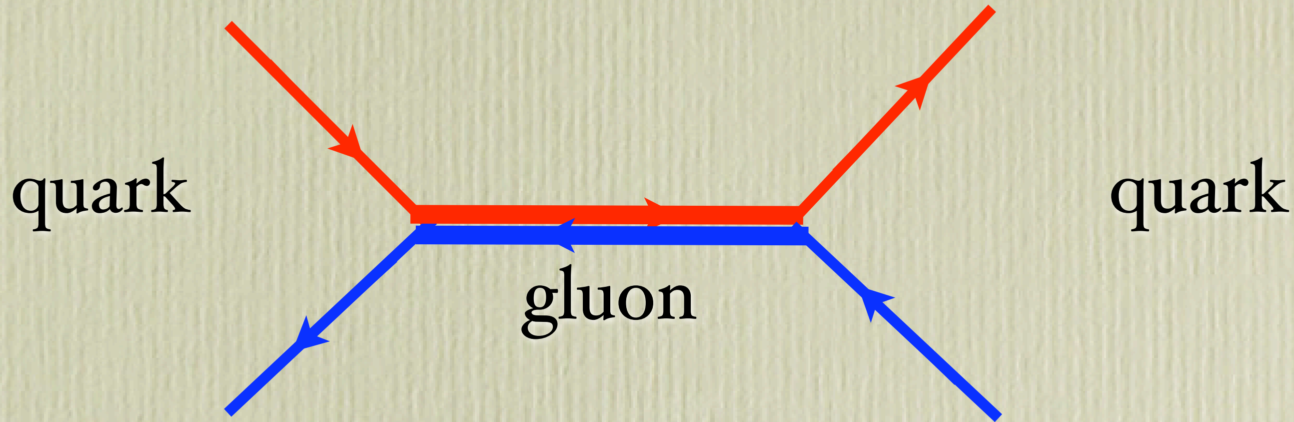
... is the quantum theory of the strong nuclear force.

- Responsible for binding quarks inside mesons and baryons:

$\pi^0, \pi^\pm, \ldots$

$p, n, \ldots$

- Quarks interact because they carry colour, which they exchange through gluons:

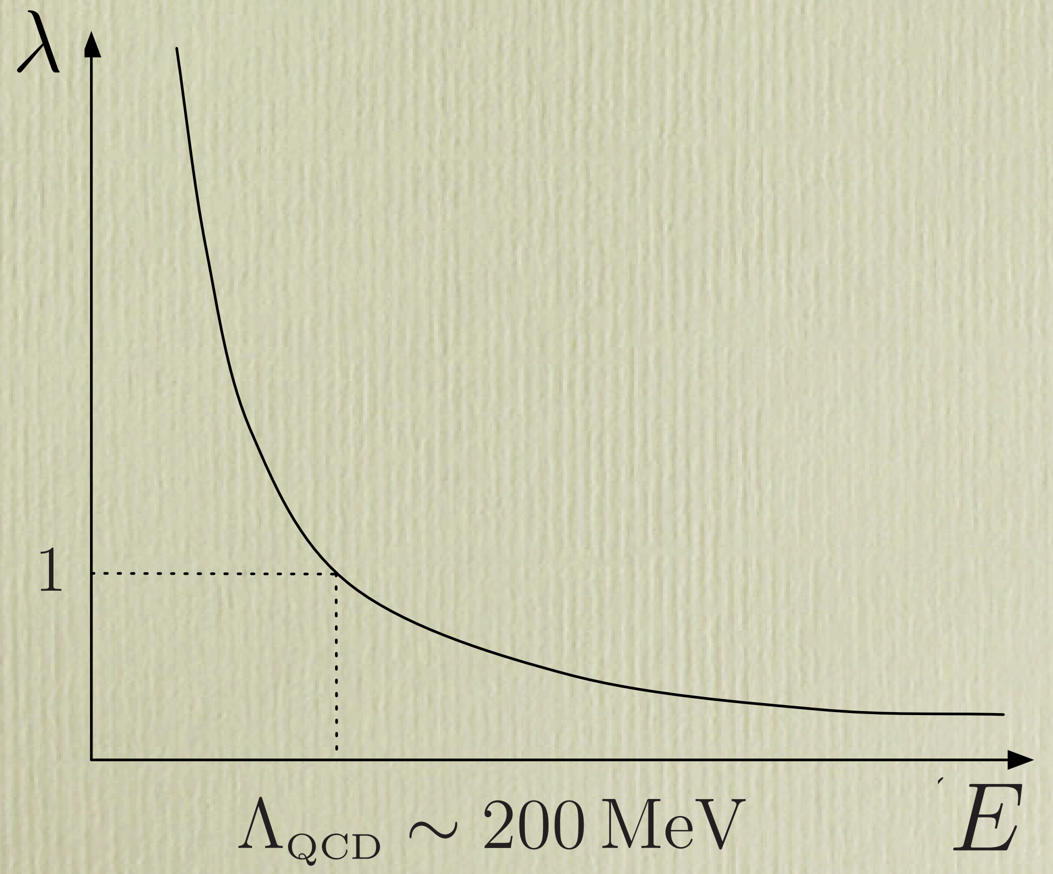


- Analogue of electric charge, but comes in $N_c = 3$ types:

$$\{\, q,\ q,\ q \,\}$$

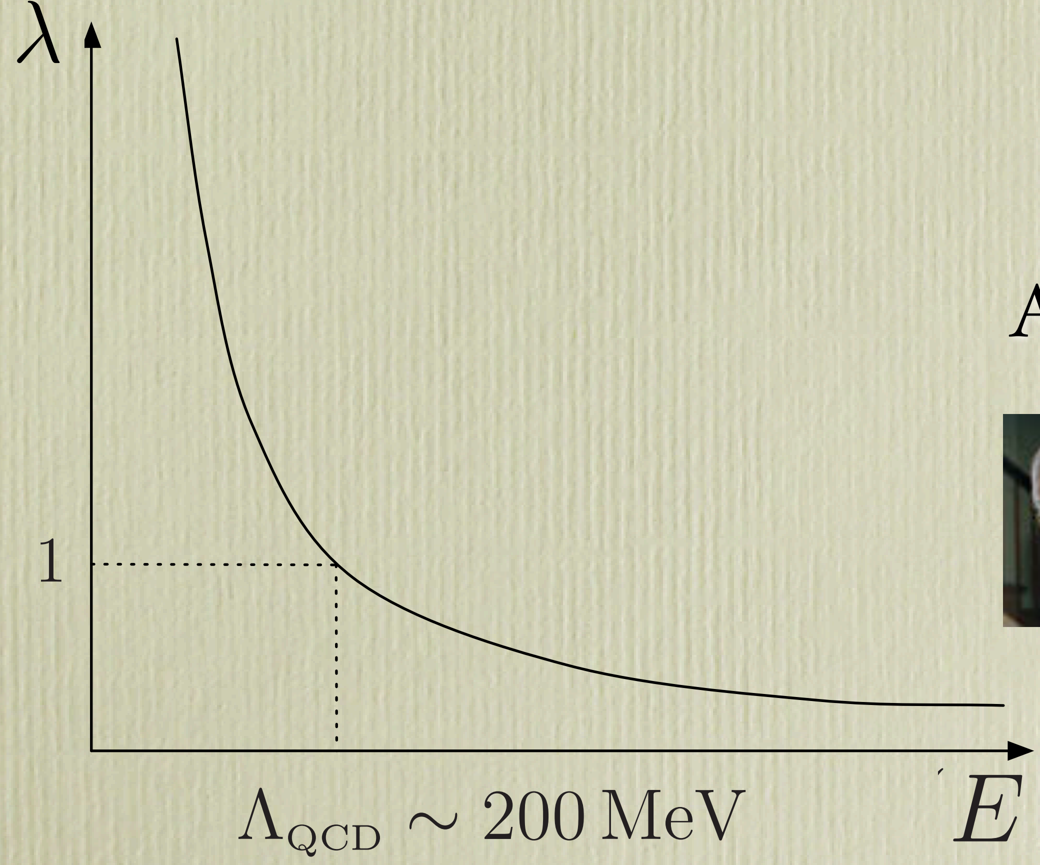
Why is QCD hard?

- Strength of interaction depends on energy:



Why is QCD hard?

Strong coupling:
No analytic and truly systematic methods!



Asymptotic freedom

The Nobel Prize in Physics 2004

D. Gross D. Politzer F. Wilczek

QCD remains a challenge after 36 years

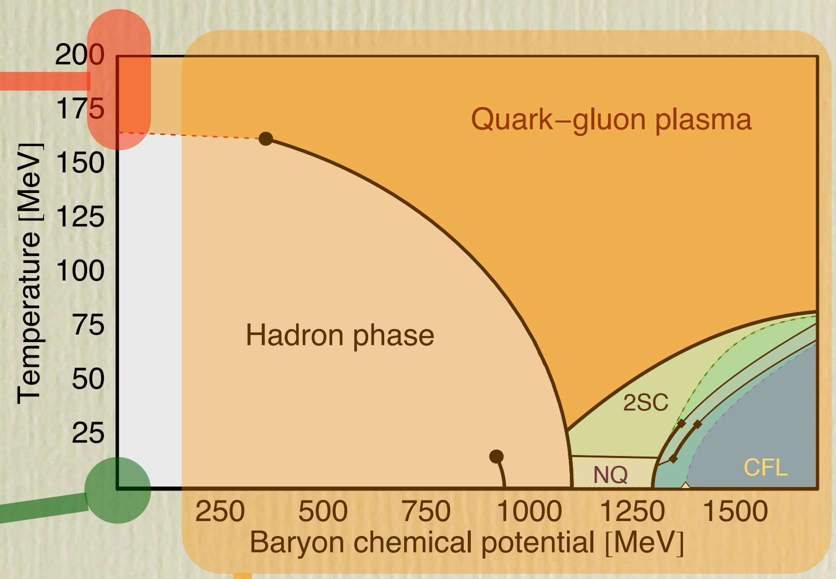
- Lattice is good for static properties, but not for real-time physics...
- ... and for a theorist it is a black box.
- A string reformulation might help.
- Topic of this talk, with focus on the QGP.

Plan for the rest of the talk

- All you need to know about string theory.
- Why and how should QCD and ST be related.
- Some results from ST (a biased list):

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

- Experimentally studied in HIC.
- Greatest impact from string theory.



More briefly on the vacuum:

$$T = 0\ ,\ \ \mu_B = 0$$

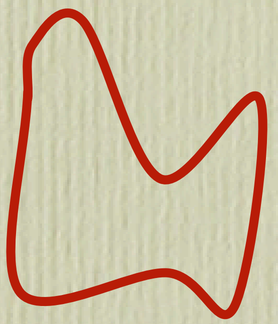
- Obvious importance.

Remarks on $\mu_B \neq 0$

- Concluding thoughts.

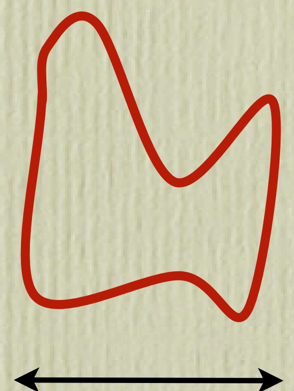
All you need to know about string theory

- String theory is a quantum theory of one-dimensional objects.

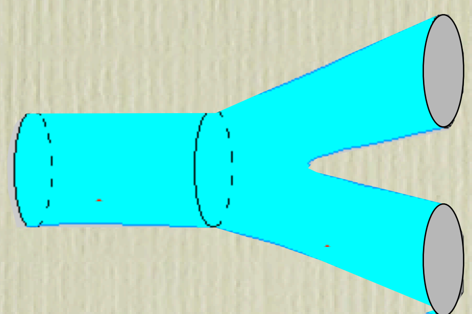


- String theory is a quantum theory of one-dimensional objects.

- Characterised by two parameters:

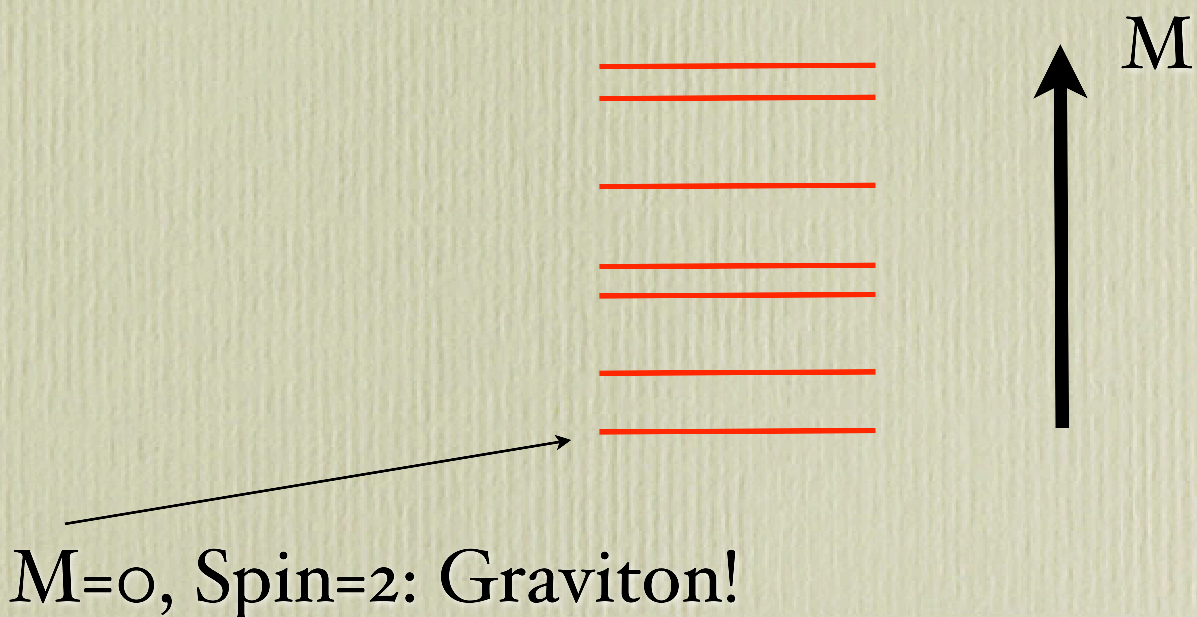


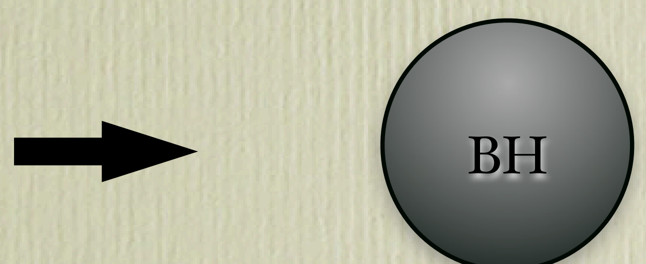
ℓ_s



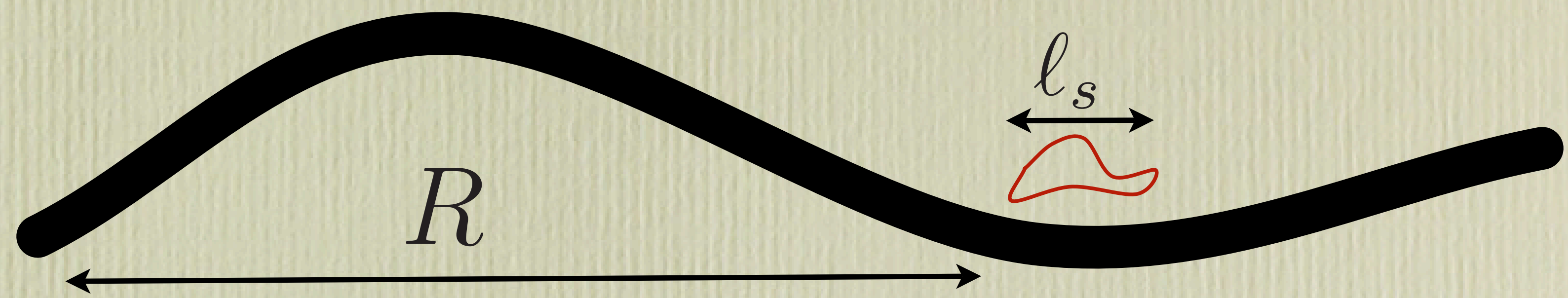
g_s

- Different vibration modes behave as particles of different masses and spins:





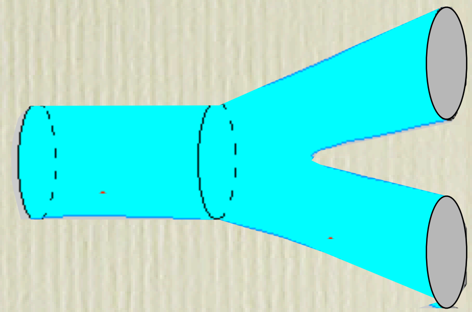
- Interested in strings propagating in curved space:



- Complicated theory, but simplifies dramatically if:

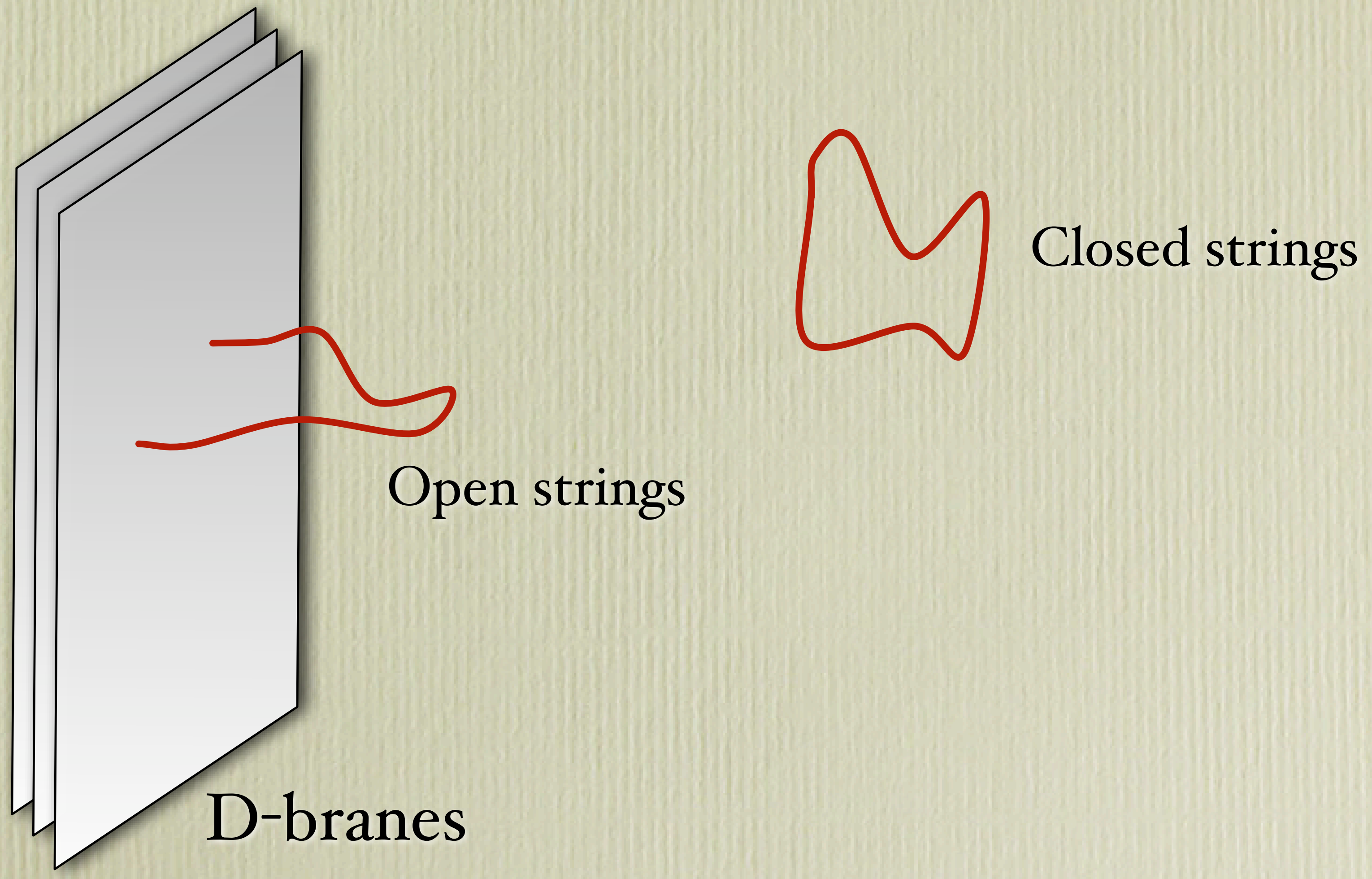
$\ell_s \ll R$: String behaves as a point.

$g_s \ll 1$: String does not split.



→ Classical supergravity.

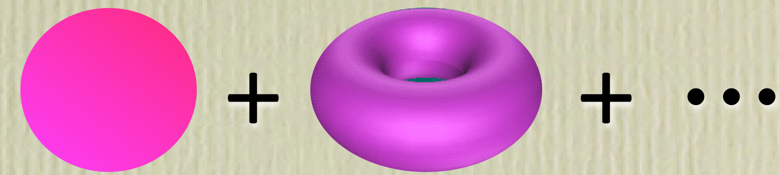
- Also contains open strings... attached to D-branes.



Why and how should QCD and string theory be related

The gauge/string duality

- Large-N_c expansion:

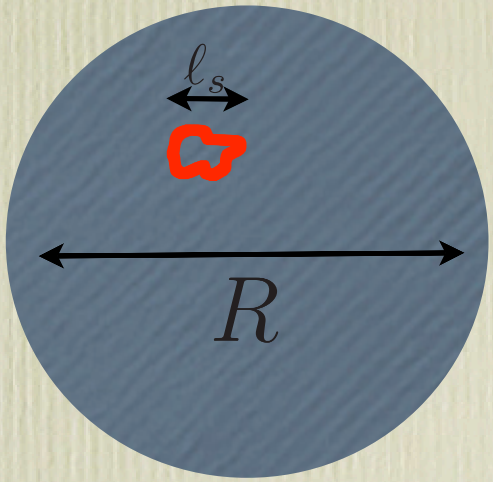


't Hooft '74

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

- First concrete example:

Maldacena '97



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

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

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

  Framework for non-perturbative gauge theory physics!

Disclaimer I: Not proven, but lots of evidence.

Why have we not solved QCD?

$$\Lambda_{\mathrm{QCD}} \sim M e^{-\frac{\#}{\lambda(M)}}$$

Decoupling: $\lambda(M) \ll 1$

Supergravity: $\lambda(M) \gg 1$

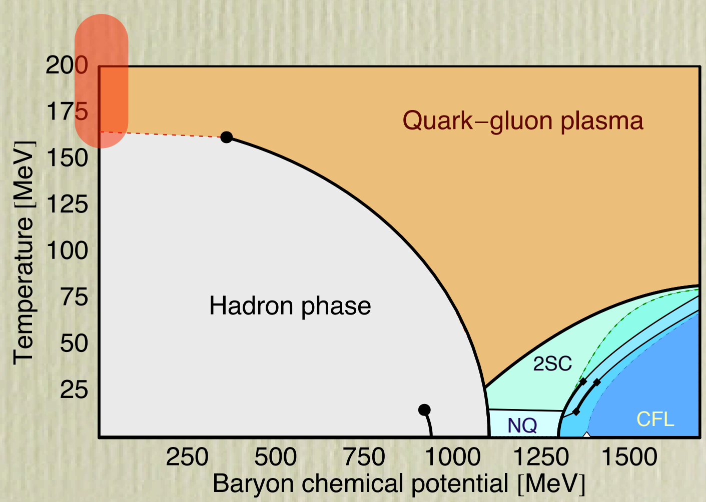
Disclaimer II:
Dual of QCD is presently inaccessible.

Therefore:

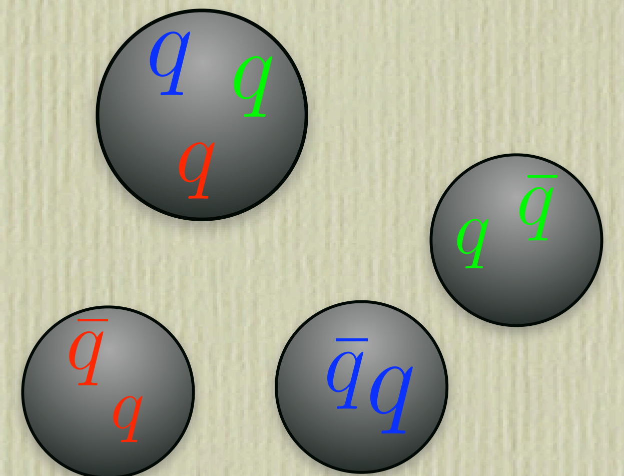
- Certain quantitative observables (eg. T=0 spectrum) will require going beyond supergravity.

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

Some results from string theory:
The QGP

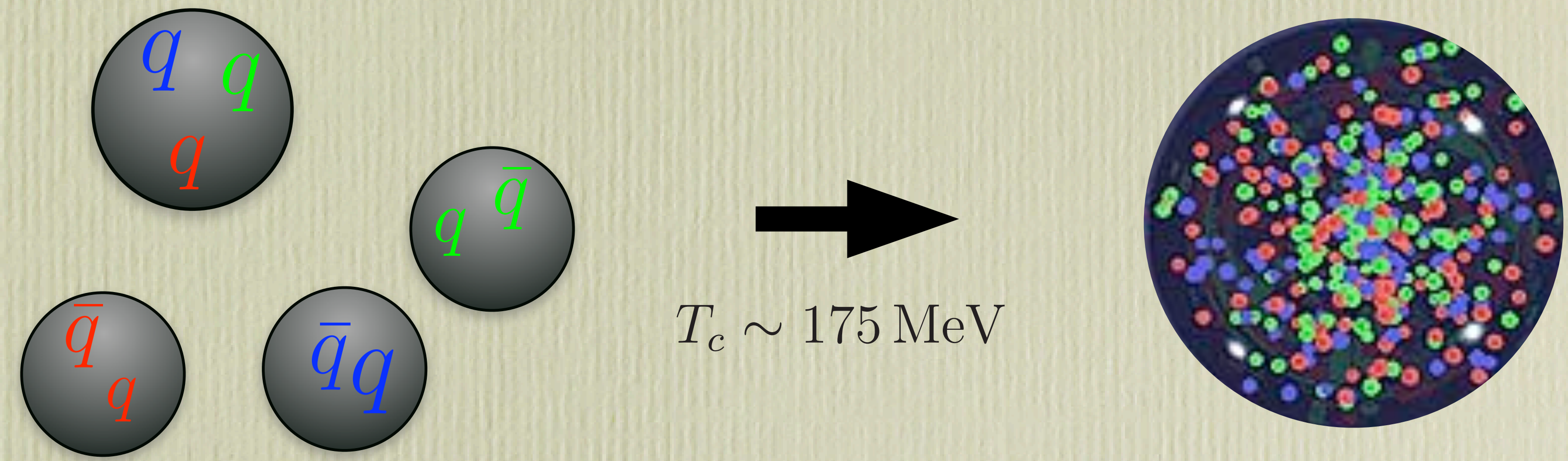


Confinement...



Mesons and baryons

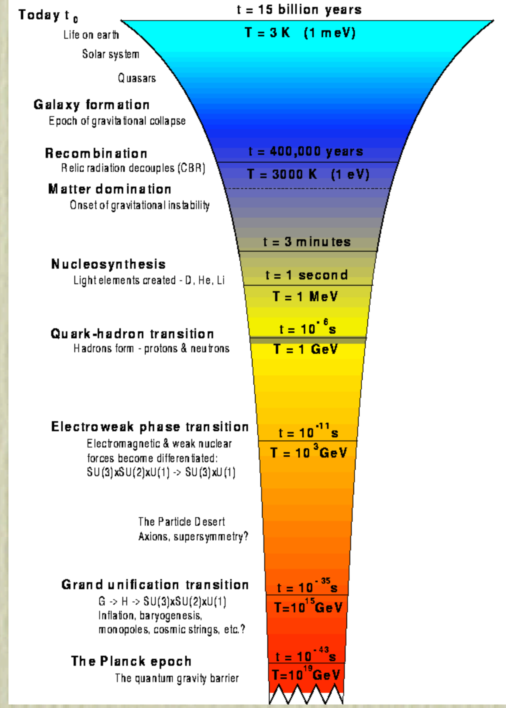
Confinement and Deconfinement



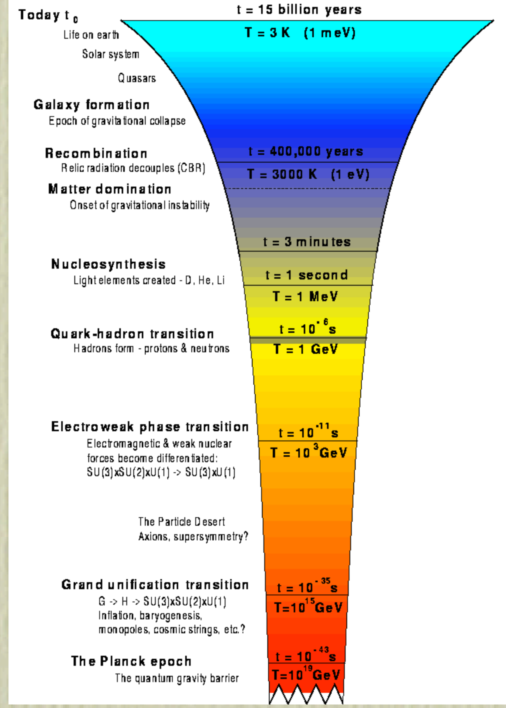
Mesons and baryons

Quark Gluon Plasma (QGP)

- This was realised in the hot, early Universe...



- This was realised in the hot, early Universe...

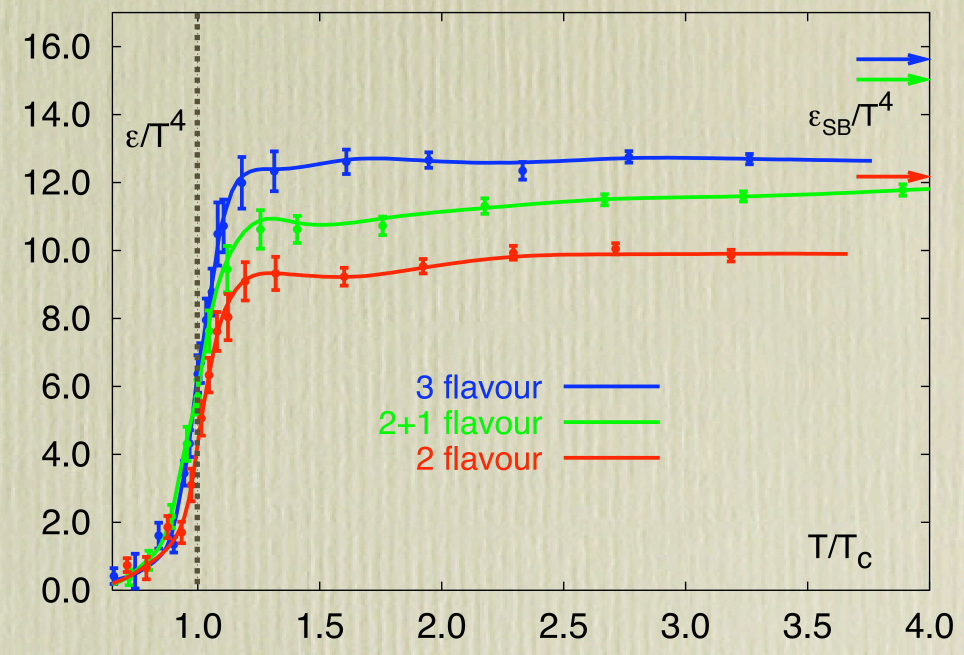


... and is the only fundamental phase transition that can be recreated in a lab like RHIC or LHC!

Good example: $\frac{\eta}{s} = \frac{1}{4\pi}$

Lattice thermodynamics:

$$E_{\text{deconf}} \sim 80\% E_{\text{ideal}}$$



Karsch, hep-lat/0106019

Interpretation:
QGP is weakly coupled

Conclusion:
η/s must be large, since in pQCD $\frac{\eta}{s} \sim \frac{1}{\lambda^2 \log \lambda}$

Arnold, Moore & Yaffe
Huot, Jeon & Moore

But, isn't this counterintuitive?

Indeed, thermodynamics can be misleading...

- For example, for N=4 SYM: $E_{\text{strong coupling}} \sim 75\% E_{\text{ideal}}$

Gubser, Klebanov & Peet

- And yet, in the limit $N_c \to \infty \, , \lambda \to \infty$ one finds:

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

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

- Similar statics, radically different dynamics.

- 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.

- Suggests that $\eta/s = 1/4\pi$ is a "universal" property of strongly coupled non-Abelian plasmas, and hence... a prediction:

If QCD just above deconfinement is strongly coupled, then $\eta/s \simeq 1/4\pi$.

- We cannot compute this, but we can go to RHIC:

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

For water $\frac{\eta}{s} \sim 380 \times \frac{1}{4\pi}$.

For liquid He $\frac{\eta}{s} \sim 9 \times \frac{1}{4\pi}$.

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

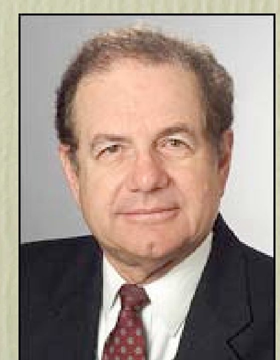
RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

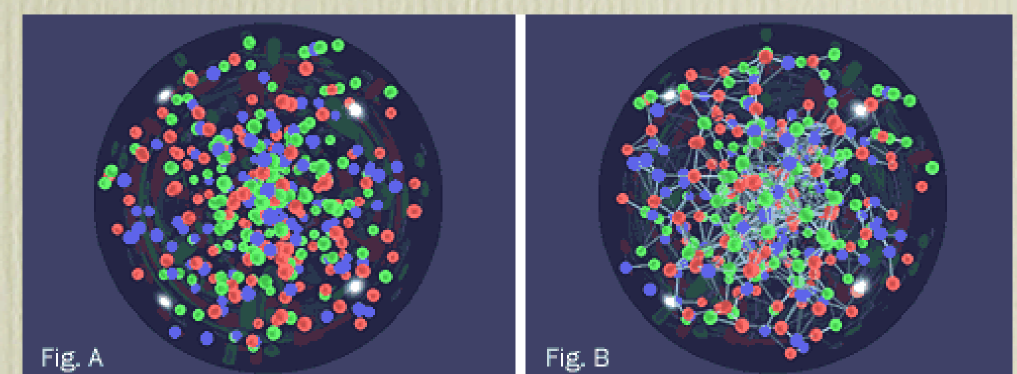
Secretary of Energy Samuel Bodman



Dr. Raymond L. Orbach

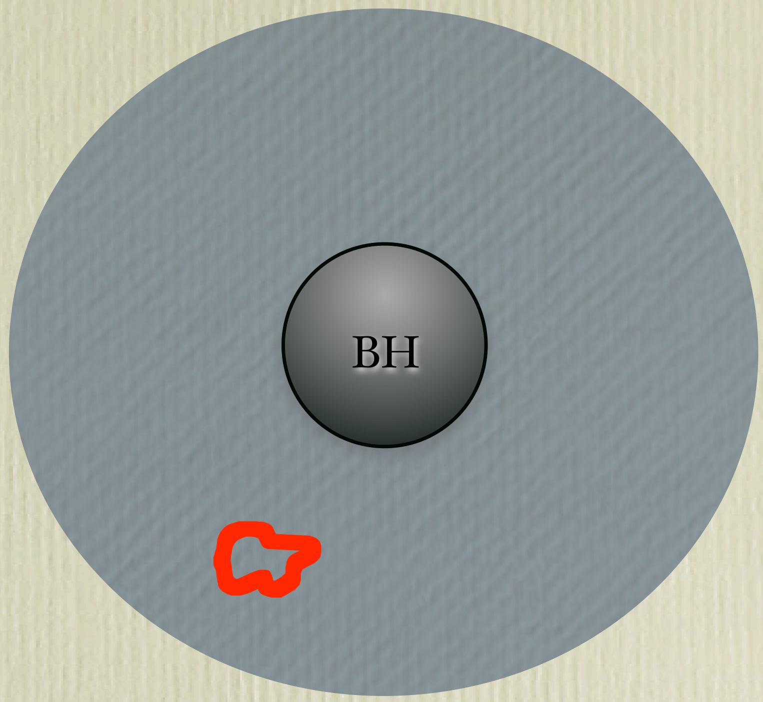
Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of **string theory**, an approach that attempts to explain fundamental properties of the universe using 10 dimensions instead of the usual three spatial dimensions plus time.

"The possibility of a connection between **string theory** and RHIC collisions is unexpected and exhilarating," Dr. Orbach said. "String theory seeks to unify the two great intellectual achievements of twentieth-century physics, general relativity and quantum mechanics, and it may well have a profound impact on the physics of the twenty-first century."



Why is the ratio universal?

Deconfined plasma ⟷



Witten '98

Entropy: $$s = \frac{A}{4G}$$

Viscosity: $$\eta = \frac{\sigma_{\rm abs}(\omega \to 0)}{16\pi G} = \frac{A}{16\pi G}$$

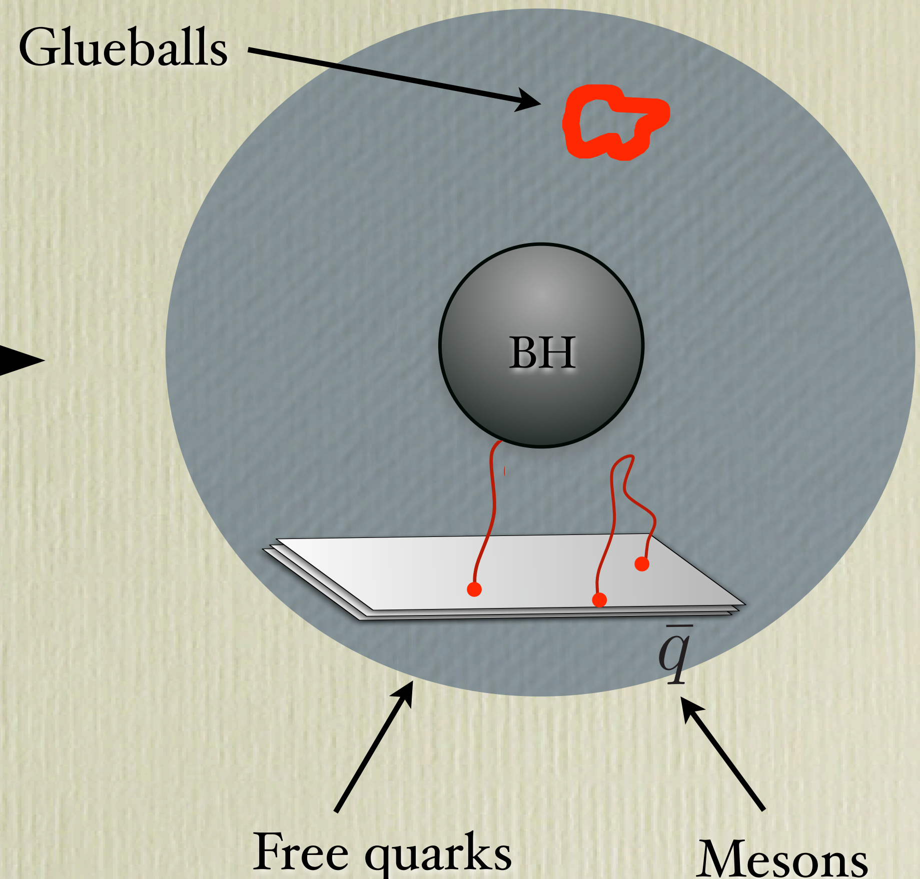
↑ gauge/gravity duality

↑ classical GR theorem

Combine with another universal property

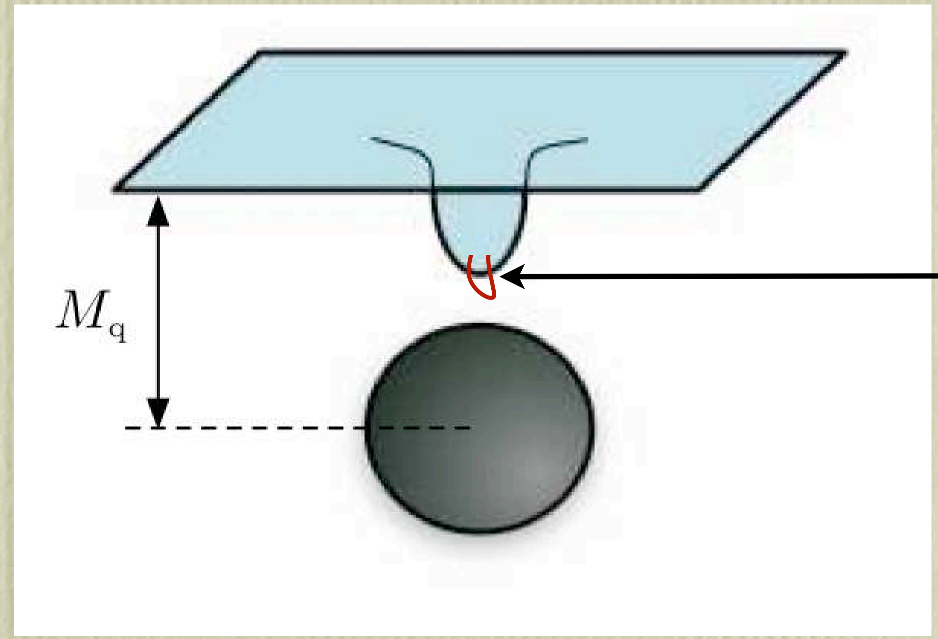
$N_f \ll N_c$ quark flavours $\longleftrightarrow$

Karch & Randall '01
Karch & Katz '02



Limiting velocity for mesons

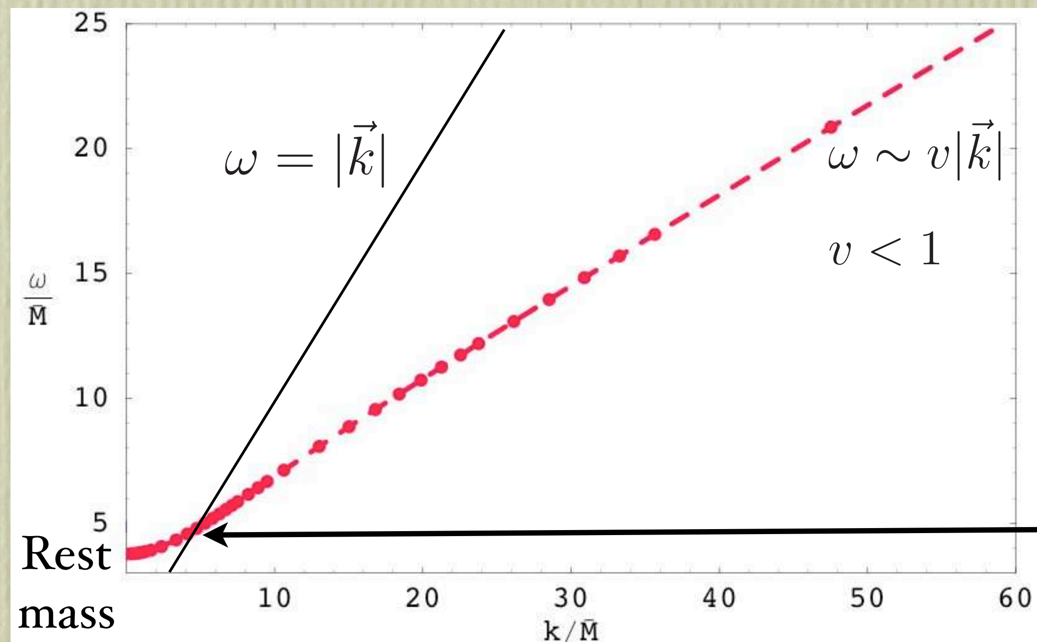
D.M., Myers & Thomson '07
Ejaz, Faulkner, Liu, Rajagopal & Wiedemann '07



Limiting velocity
=
Local speed of light at the tip

Peak in photon spectrum

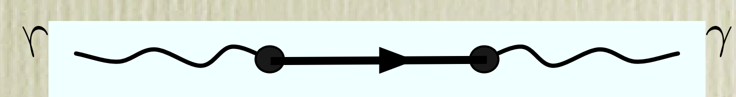
D.M., Patiño-Jaidar '07
Casalderey-Solana, D.M. '08



Meson with $\omega^2 = k^2$ has same quantum numbers as a photon

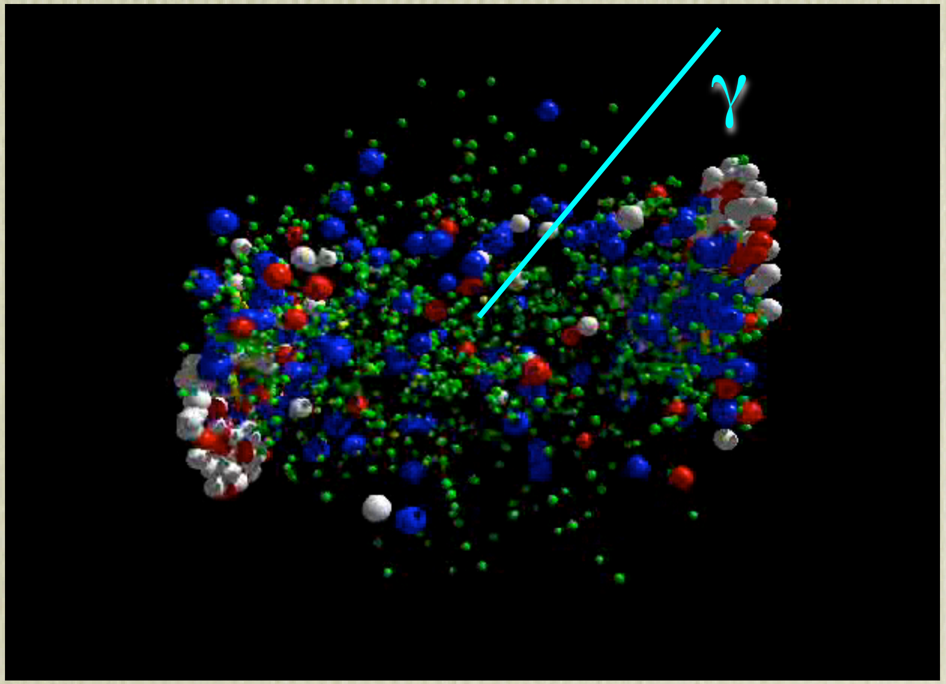
Produces resonance peak in photon 2-point function and hence in thermal photon spectrum:

$$\langle J_\mu^{EM} J_\nu^{EM} \rangle \sim$$



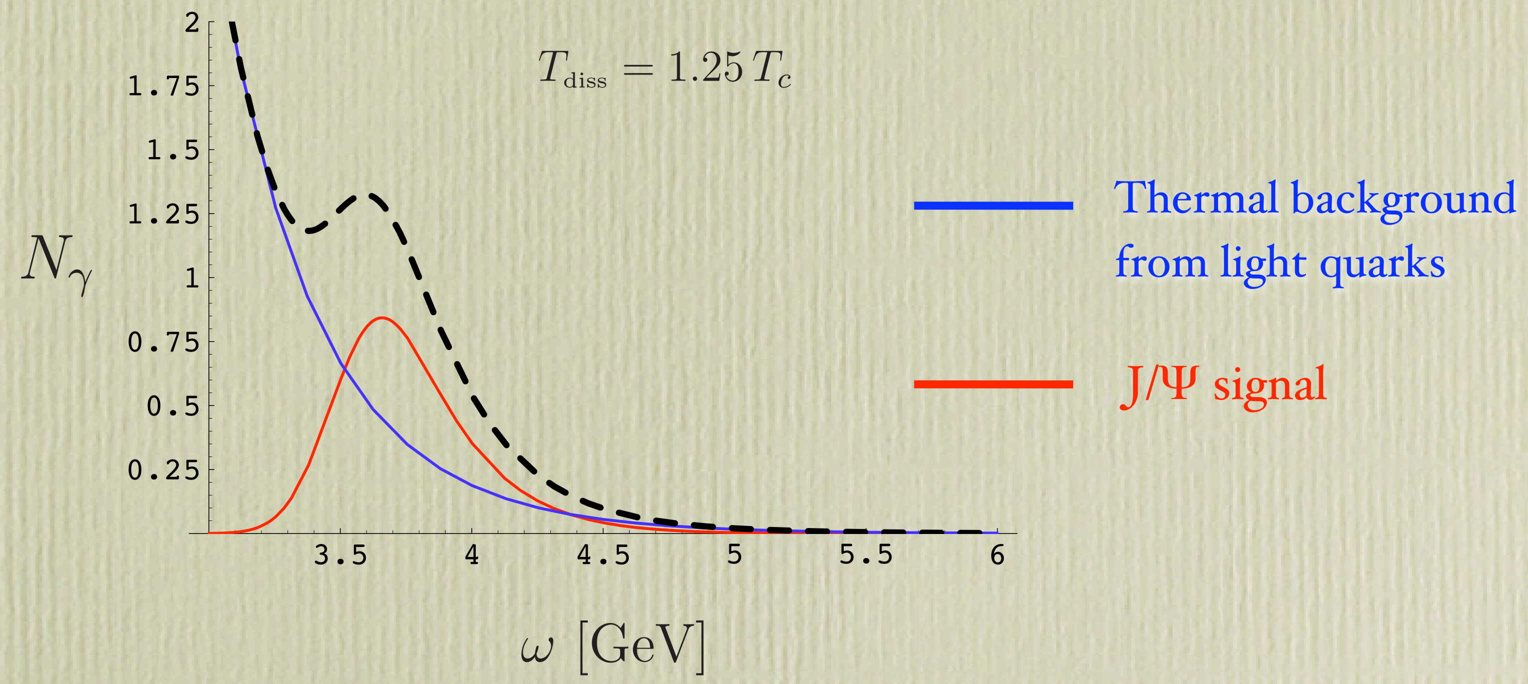
Peak in photon spectrum

- This is interesting because QGP is optically thin
  → Thermal photons carry valuable information.



Peak in photon spectrum

- Eg. a simple model for J/Ψ at LHC energies yields:



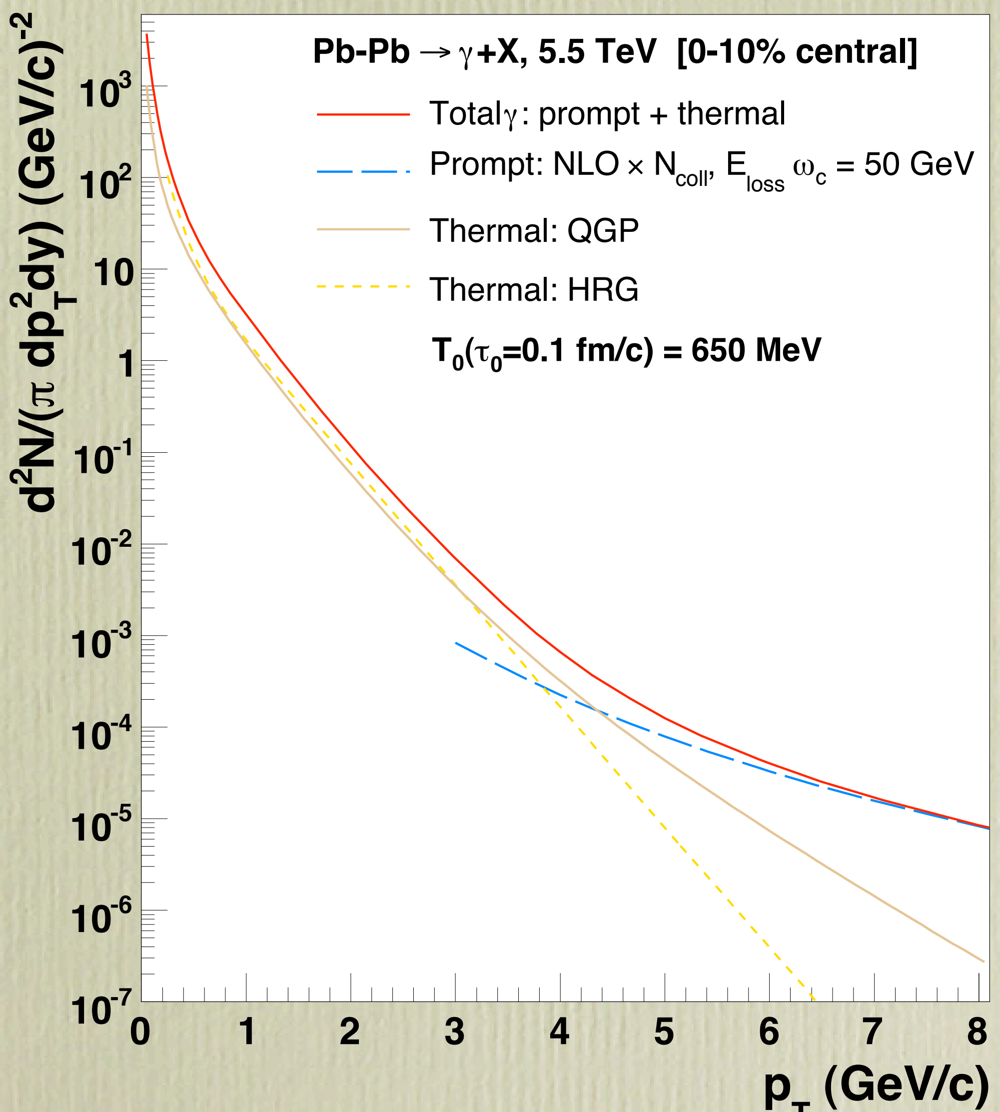
- Quadratically sensitive to $c\bar{c}$ cross-section -- not observable at RHIC.

- Location of the peak between 3-5 GeV.

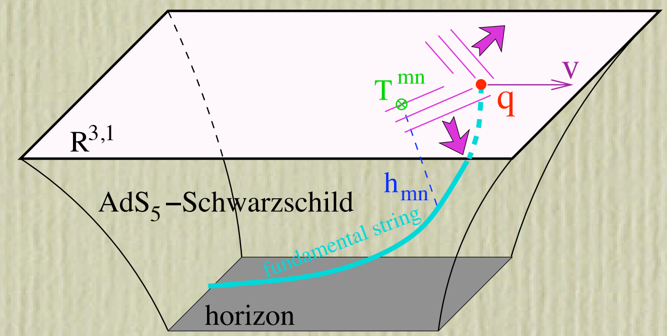
Peak in photon spectrum

- Signal is also comparable (or larger) than pQCD background:

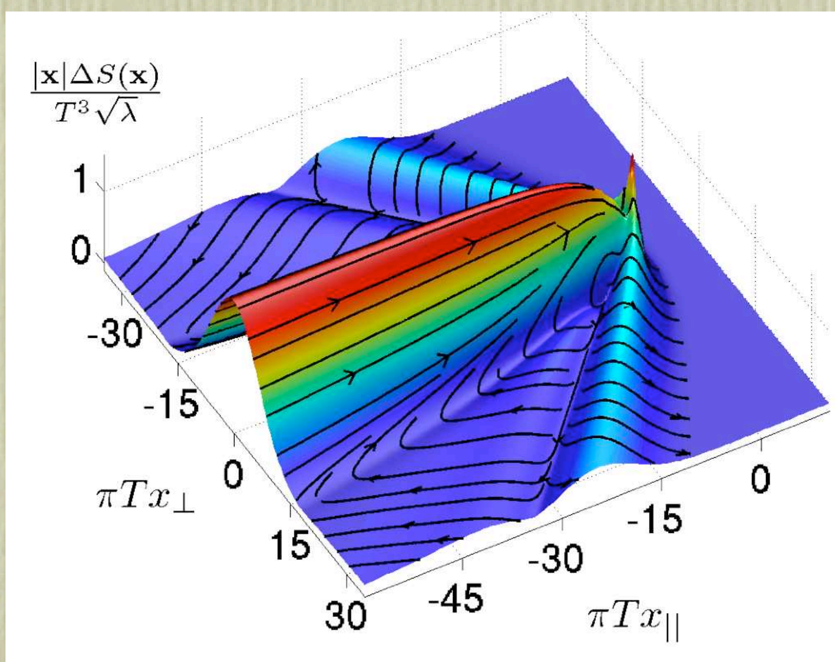
Arleo, d'Enterria and Peressounko '07

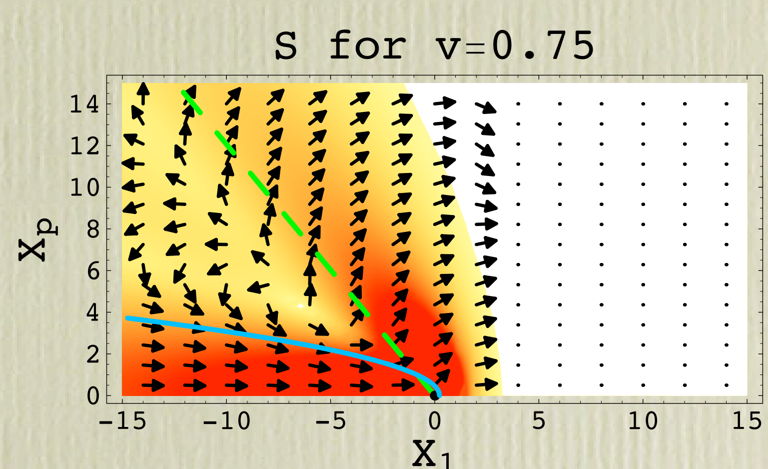


Quark energy loss through drag



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



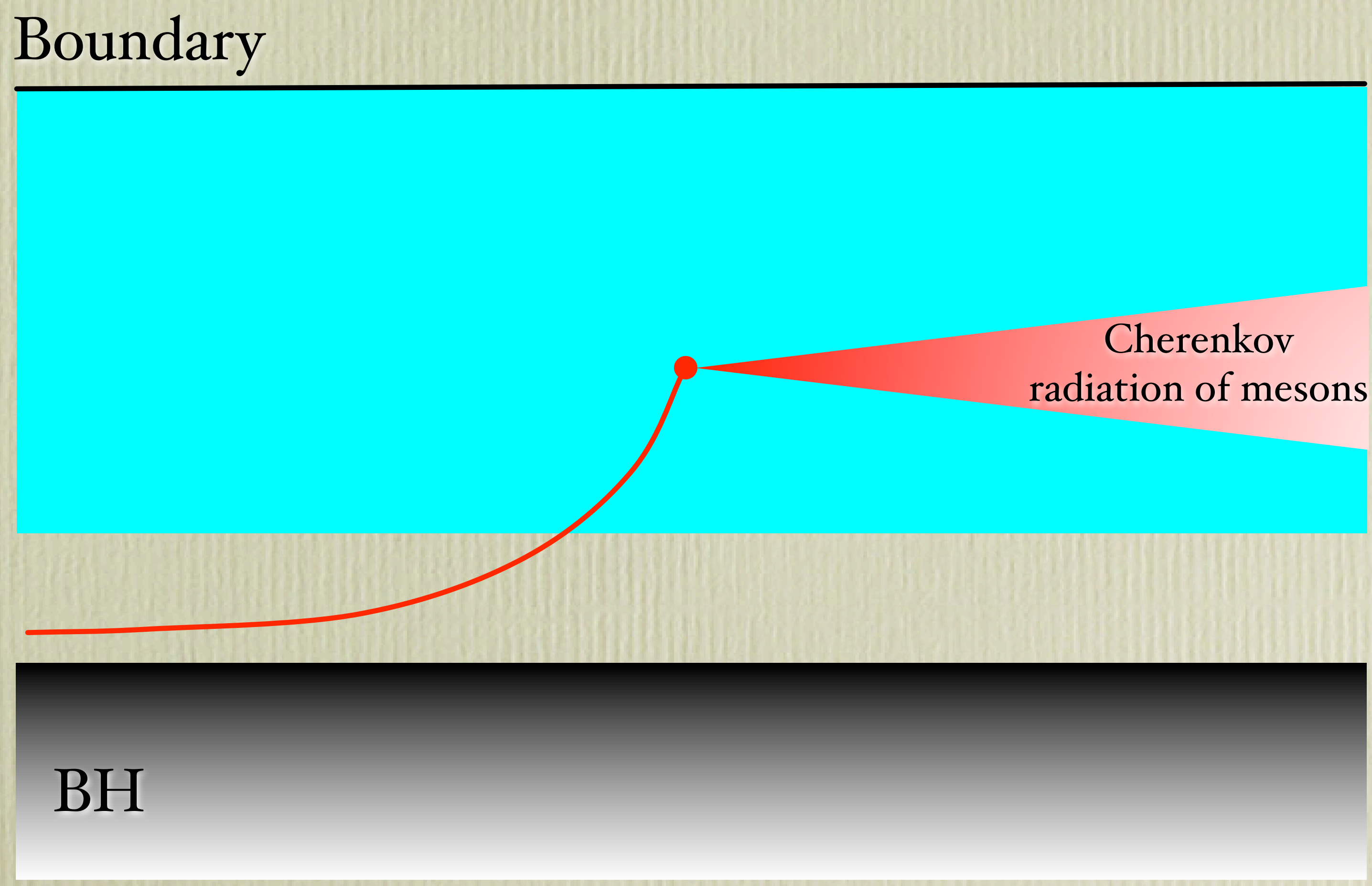


Friess, Gubser & Michalogiorgakis '06
Friess, Gubser, Michalogiorgakis & Pufu '06
Gubser & Pufu '07
Gubser, Pufu & Yarom '07
Yarom '07
Chessler & Yaffe '07

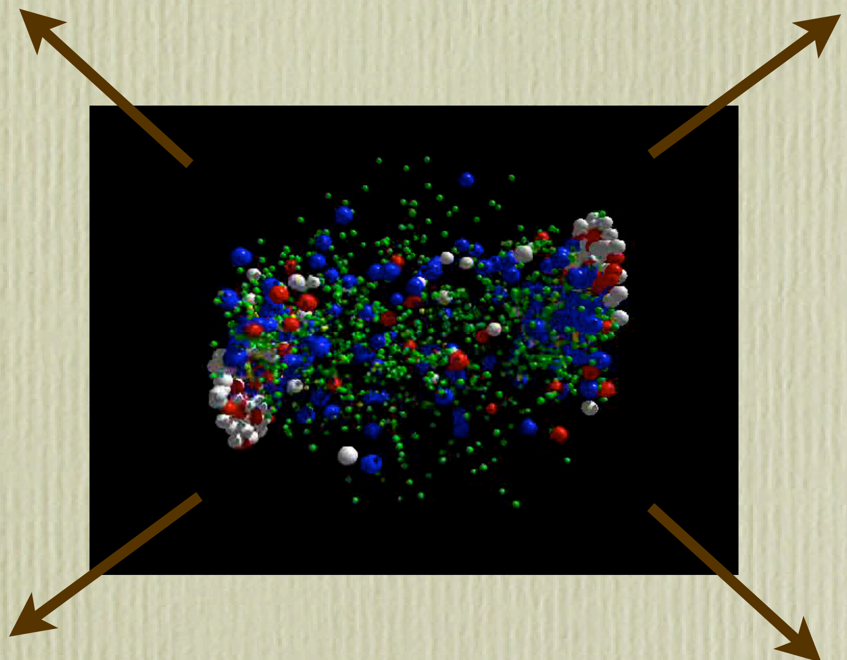
A new mechanism for quark energy loss

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

(this afternoon)

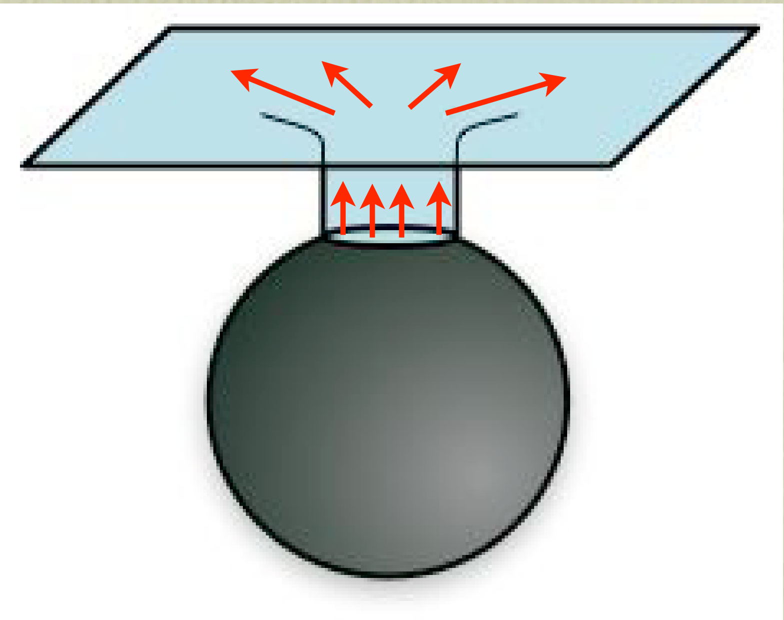


Expanding plasmas



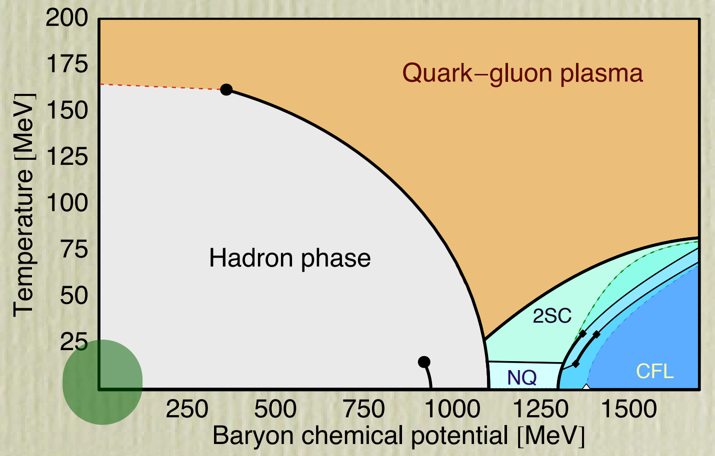
Janik & Peschanski '05
Janik & Peschanski '06
Kajantie & Tahkokallio '06
Janik '06
Sin, Nakamura & Kim '06
Nakamura & Sin '06
Friess, Gubser, Michalogiorgakis & Pufu '06
Heller & Janik '07
Benicasa, Buchel, Heller & Janik '07
Kovchegov & Taliotis '07
Bhattacharyya, Hubeny, Minwalla & Rangamani '07
Buchel '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

Mesons and quarks in external E&M fields



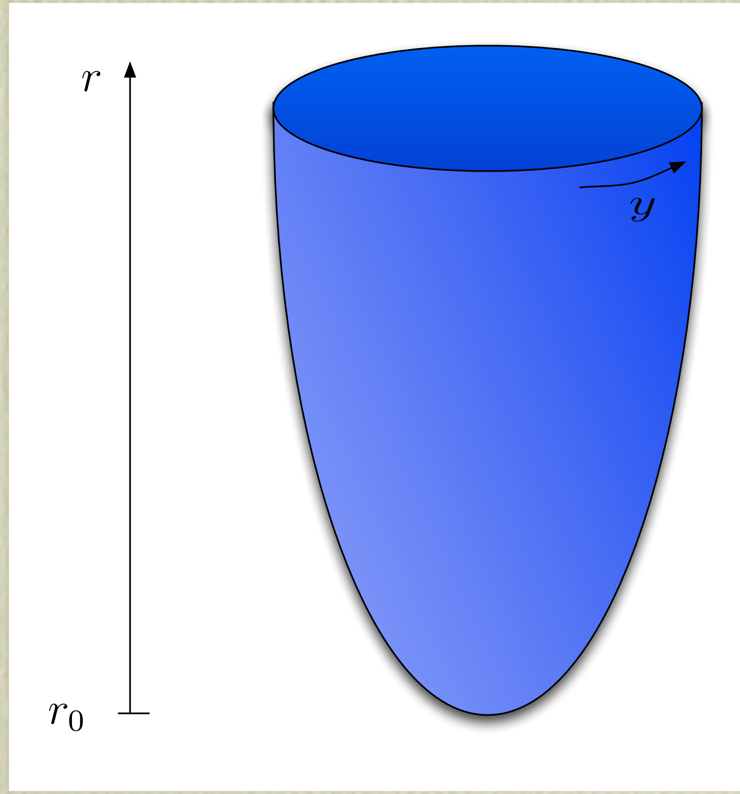
Filev, Johnson, Rashkov & Viswanathan ‘ 07
Erdmenger, Meyer & Shock ’07
Albash, Filev, Johnson & Kundu ’07
Karch & O’Bannon ‘07
Johnson & Kundu ’08
Jensen, Karch & Price ‘08
Bergman, Lifschytz & Lippert ’08
Rebhan, Schmitt & Stricker ’09
Filev, Johnson & Shock ’09
Johnson & Kundu ‘09

Some results from string theory:
The vacuum



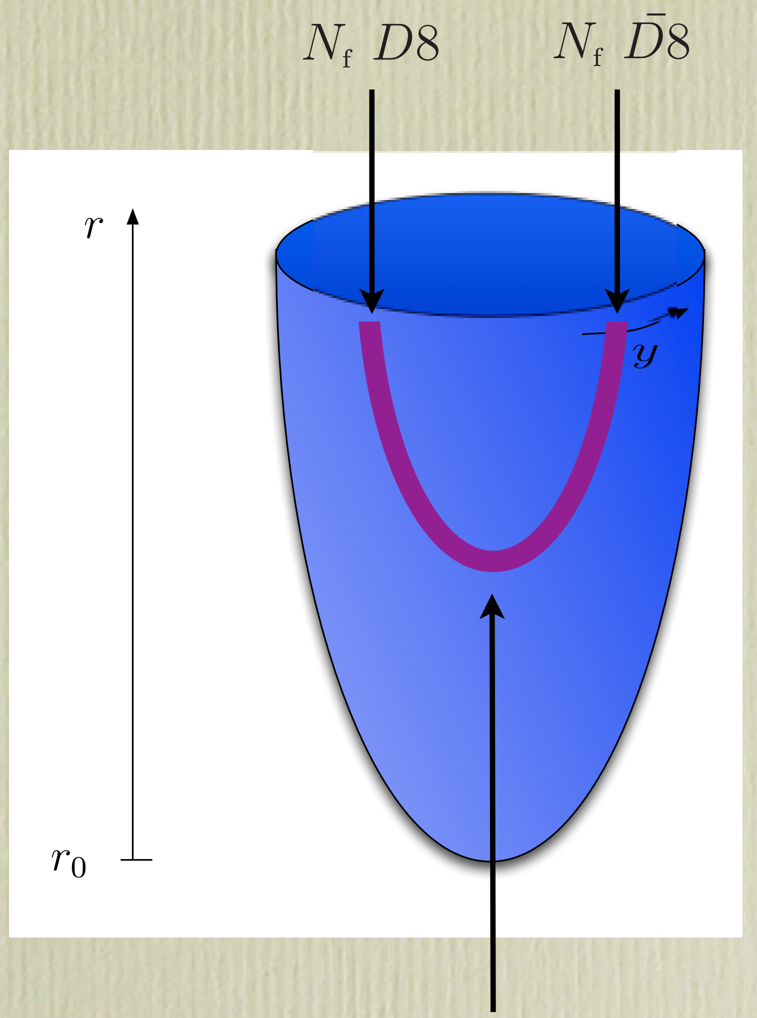
Two fundamental properties:
Confinement

Witten '98



Two fundamental properties: Confinement & SχSB

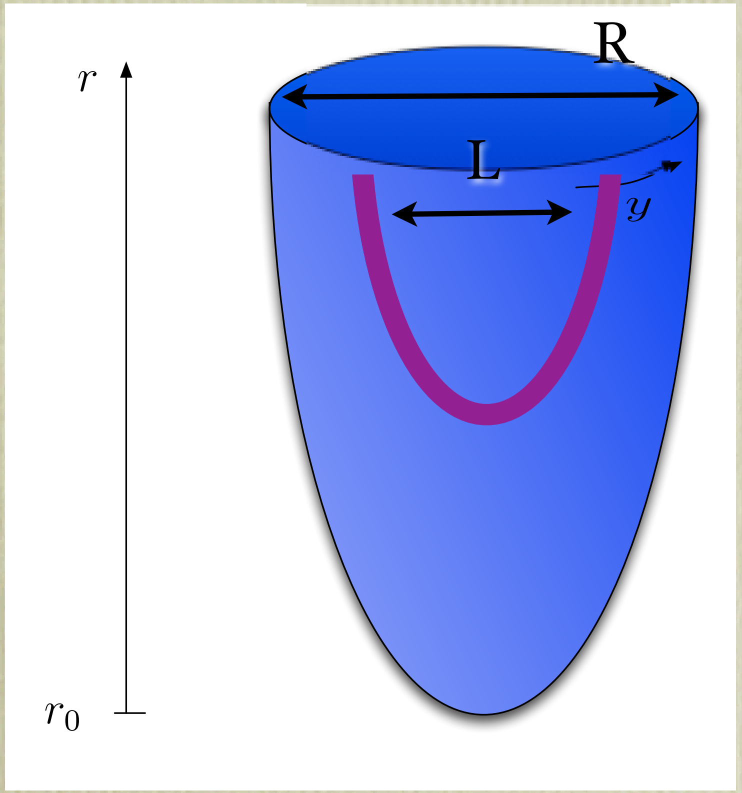
Witten '98 Sakai & Sugimoto '04



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

Comments

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



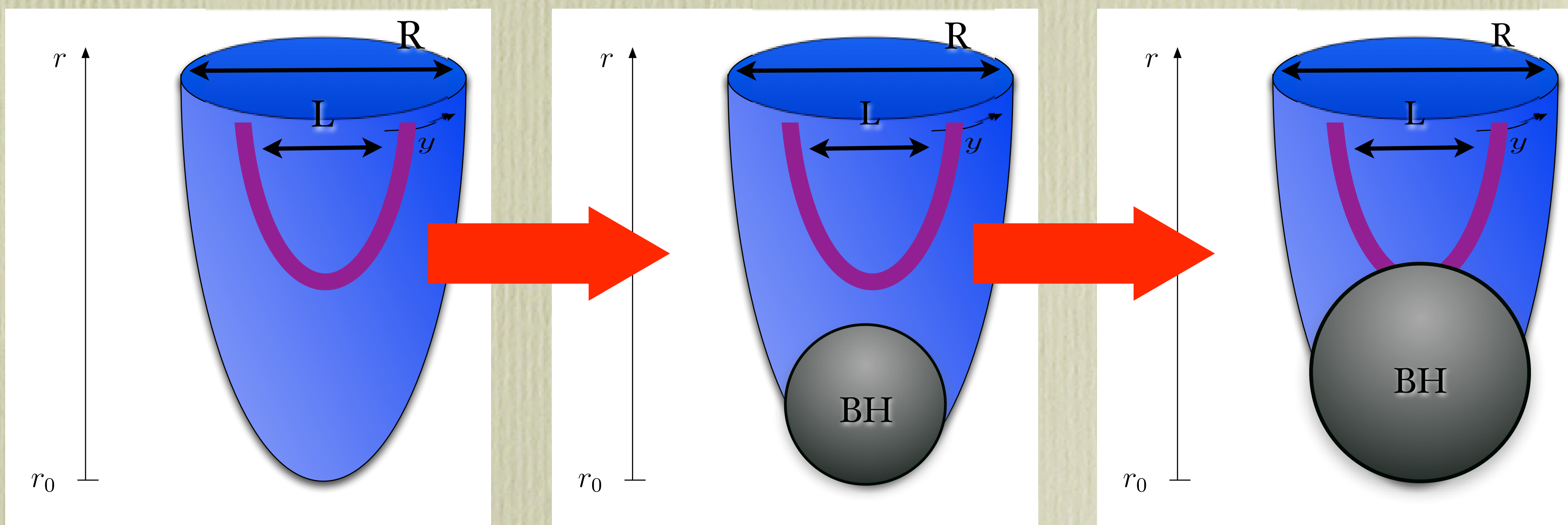
$$\Lambda_{\rm QCD} \sim M_{\rm glueball} \sim M_{\rm KK} \sim 1/R$$

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

Comments

- Can be seen by turning on temperature:

Aharony, Sonnenschein & Yankielowicz '06
Parnachev & Sahakyan '06



Deconfinement at T_c

Chiral symmetry restoration at $T_\chi \geq T_c$

Comments

- "Verified" on the lattice:

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

D. K. Sinclair

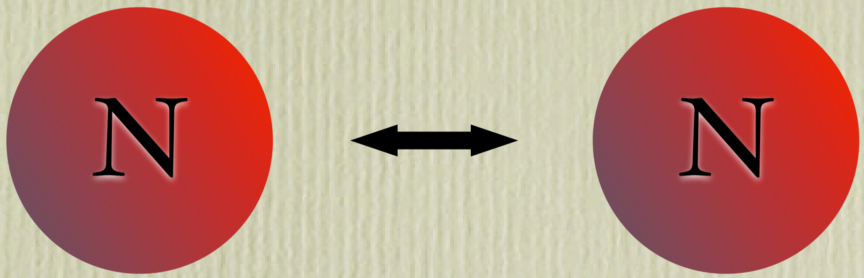
HEP Division and Joint Theory Institute, Argonne National Laboratory,

9700 South Cass Avenue, Argonne, IL 60439, USA

Abstract

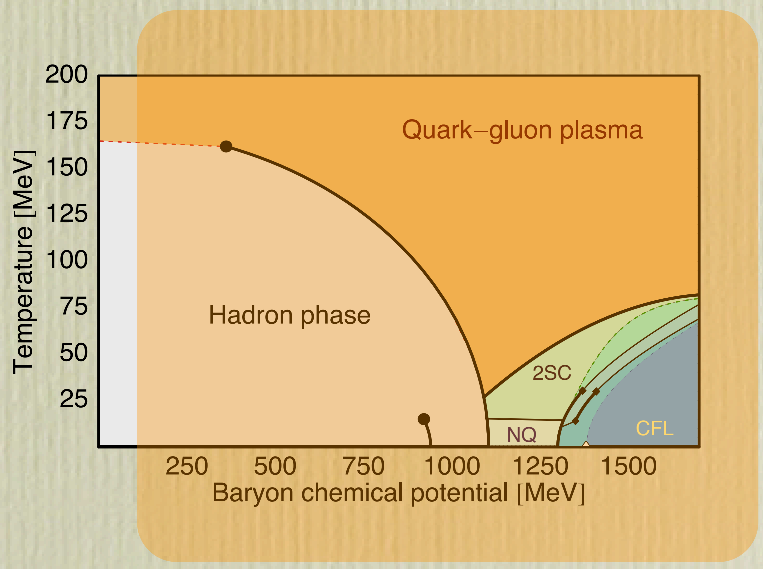
Suggested holographic duals of QCD, based on AdS/CFT duality, predict that one should be able to vary the scales of colour confinement and chiral-symmetry breaking independently. Furthermore they suggest that such independent variation of scales can be achieved by the inclusion of extra 4-fermion interactions 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.

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

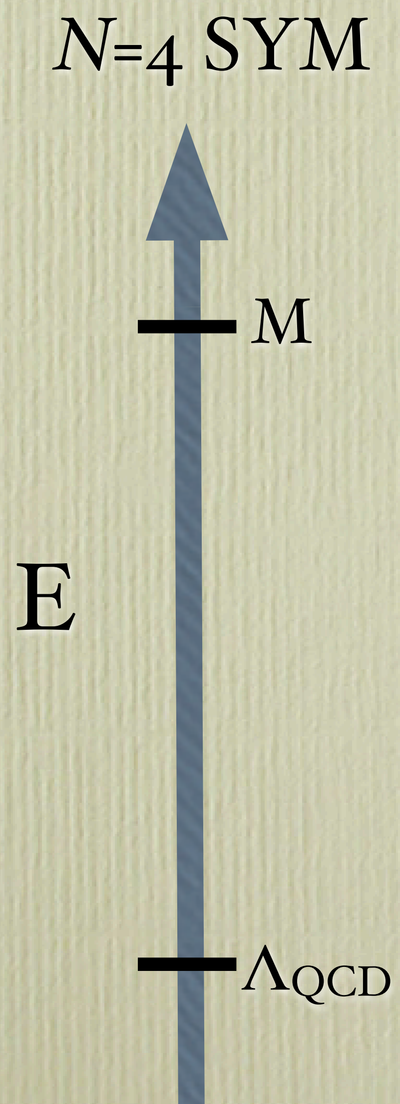
  - Fortunately, S&S does not.

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 may be very different !
  - However, see CFL phase in Chen, Hashimoto & Matsuura '09

Concluding thoughts

Is SUGRA good or bad?



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

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.