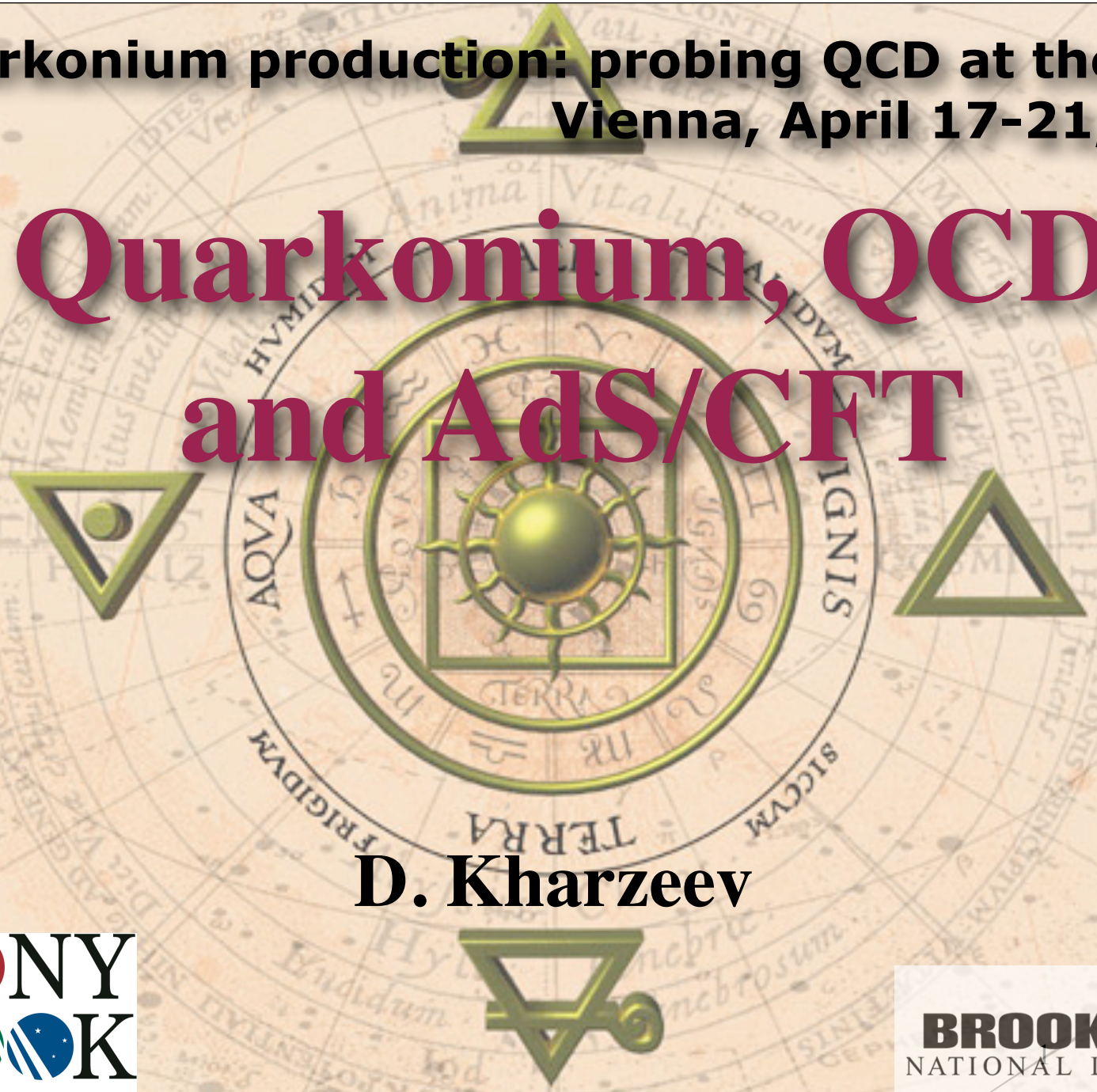
Quarkonium production: probing QCD at the LHC,
Vienna, April 17-21, 2011

# Quarkonium, QCD and AdS/CFT

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# Outline

- The beginnings

  From atoms (V century B.C.) to quarks;
  atoms, void and geometry
- The successes

  Symmetry; QCD as the gauge theory of strong interactions;
  asymptotic freedom; hard processes; strong color fields
- The challenges

  Confinement; chiral symmetry breaking; extreme QCD:
  temperature, density, energy; the spin; void and geometry
- The future

  **From particles to fields: collective phenomena**
  **as the essence of QCD; quarkonium as a probe**

# The beginnings

Λεύκιππος

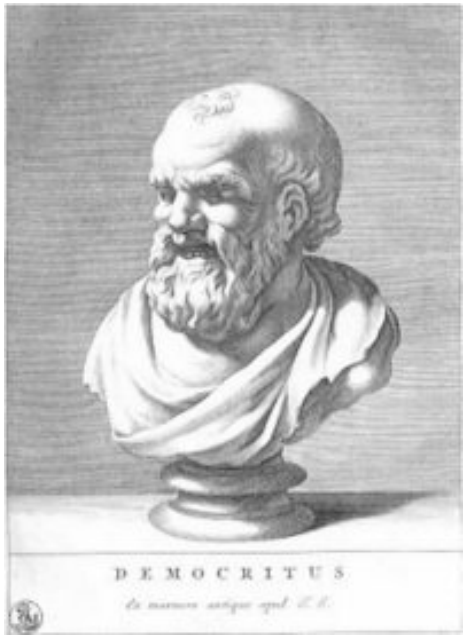
Leucippus, V B.C.

**Everything consists of**

**Atoms and Void**

ἄτομος un - cuttable, indivisible

α- τέμνω



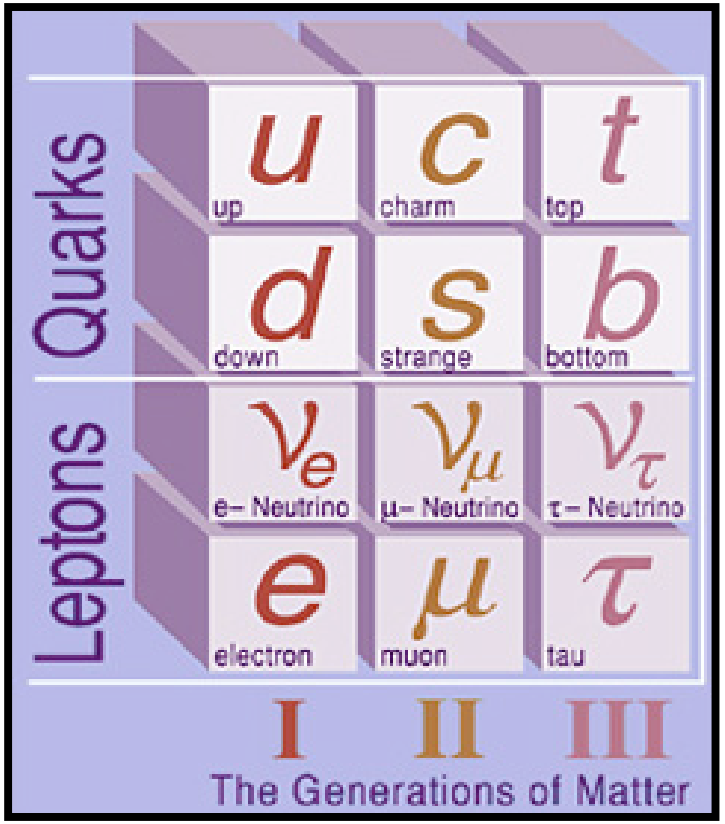

Δημόκριτος

Democritus, ca 460 -370 B.C.

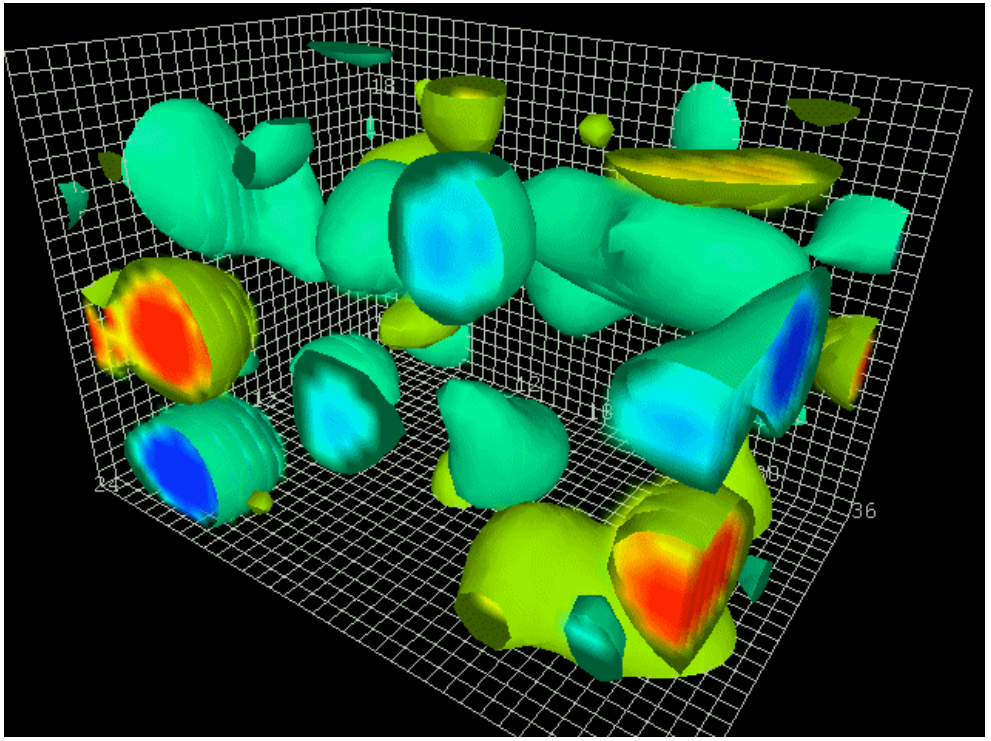
# Everything consists of

## Atoms and Void

**"Atoms",**
**ca 2011 A.D.**




**Void,**
**ca 2011 A.D.**

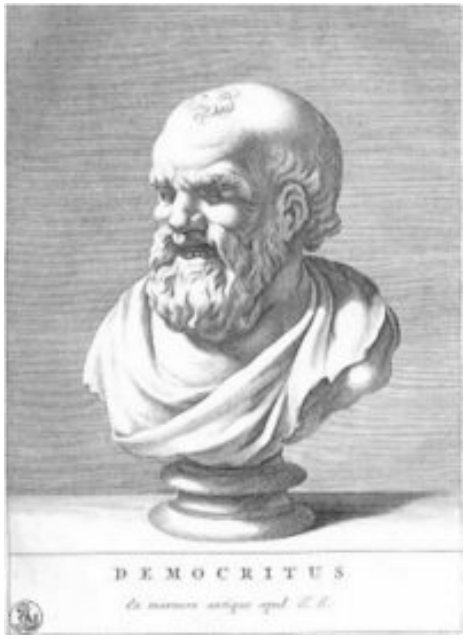


# Atomism vs corpuscularianism:

## are quarks and leptons the ultimate indivisible "atoms"of Nature?

Leucippus, V B.C.

Robert Boyle (1627–1691)



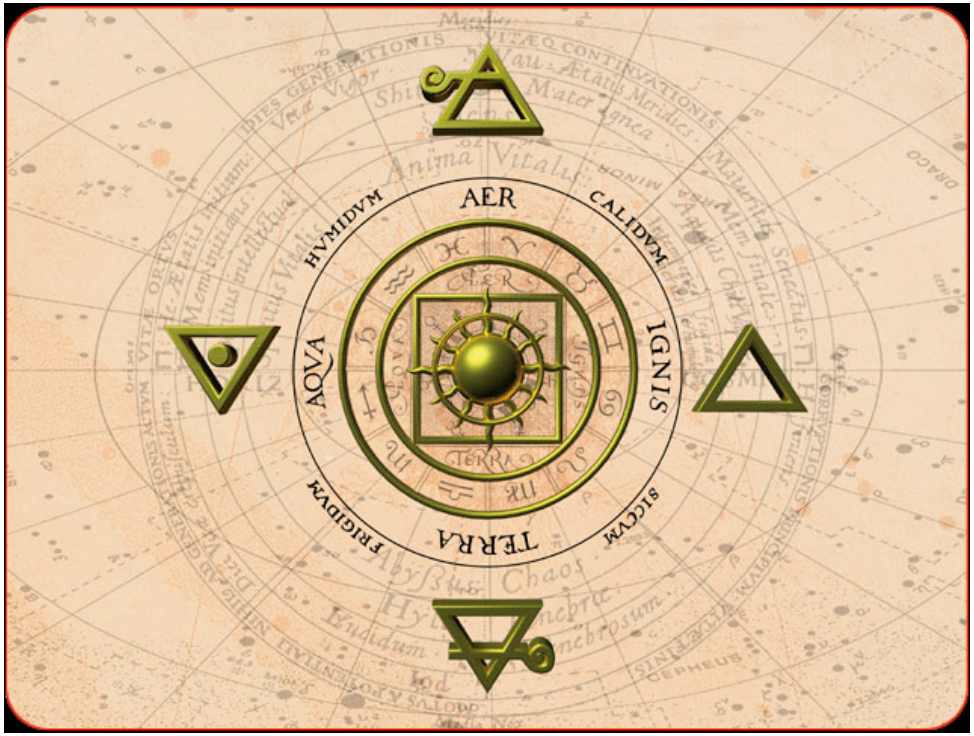

Democritus, ca 460 -370 B.C.

Page from alchemic treatise of Ramon Llull, 16th century

# Atoms and Geometry, IV B.C.

Πλάτων

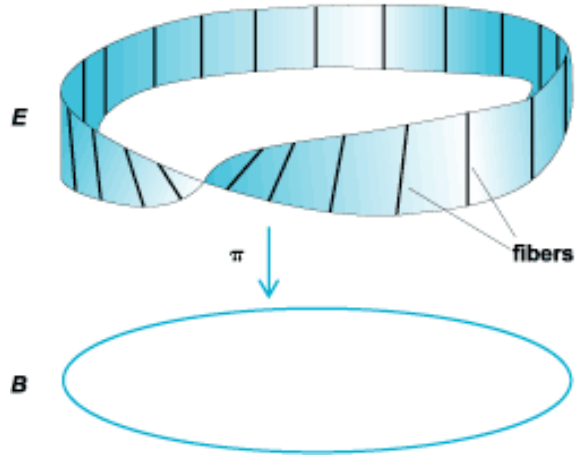
Plato, 428-348 B.C.




**Fire** **Air** **Water** **Earth**

# Atoms and Geometry, 2010 A.D.

| Geometry | ⟷ | Physics |
|---|---|---|
| Riemannian connection | ⟷ | Gauge field |
| Curvature tensor | ⟷ | Field strength tensor |




*Möbius strip, the simplest nontrivial example of a fiber bundle*

Gauge theories "live" in a fiber bundle space that possesses non-trivial topology (knots, links, twists,...)

# AdS/CFT Correspondence: Conformal gauge theory is dual to gravity

The chain of ideas:

1. String model pre-dates QCD as a description of hadron spectrum and hadron scattering amplitudes
   (Regge poles, Veneziano amplitude, Hagedorn spectrum,…)

2. Quantum theory of strings cannot be made consistent in (3+1) dimensions; the minimum number of dimensions is 5.
   Also: massless spin 2 state - graviton?

3. It has long been expected that QCD in the strong coupling and large N is described by string theory
   (at large N, planar diagrams dominate;
   they describe worldsheets of strings)

4. How to make this string description consistent
   on the quantum level?
   Add a 5th dimension to QCD and let gravity live there
   BUT: what is the metric?

$$ds^2 = R^2 \; w^2(z) \; (dx^2_{3+1} + dz^2)$$

what is the form of w(z)?

5. Consider instead a conformal theory, such as maximally super-symmetric N=4 Yang-Mills; then the requirement of conformal invariance fixes the metric of the 5th dimension uniquely - it is an Anti- de Sitter space $AdS_5$:
   invariance w.r.t. $x \rightarrow \lambda x$ fixes $w(z) = \frac{1}{z}$
   supersymmetry - $S_5$, so the theory lives in $AdS_5 \times S_5$

J.Maldacena

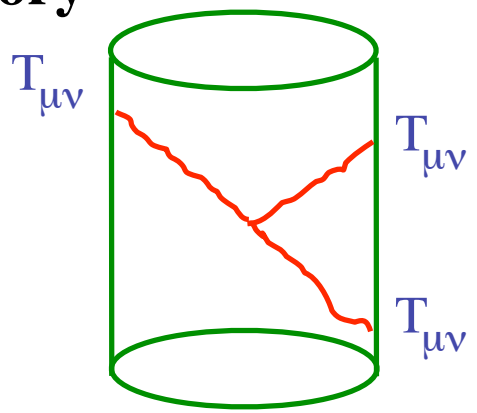
| $N = 4$ SU(N) Yang-Mills theory | = | String theory on $AdS_5 \times S^5$ |
|---|---|---|

Radius of curvature $$R_{S^5} = R_{AdS_5} = \left(g_{YM}^2 N\right)^{1/4} l_s$$

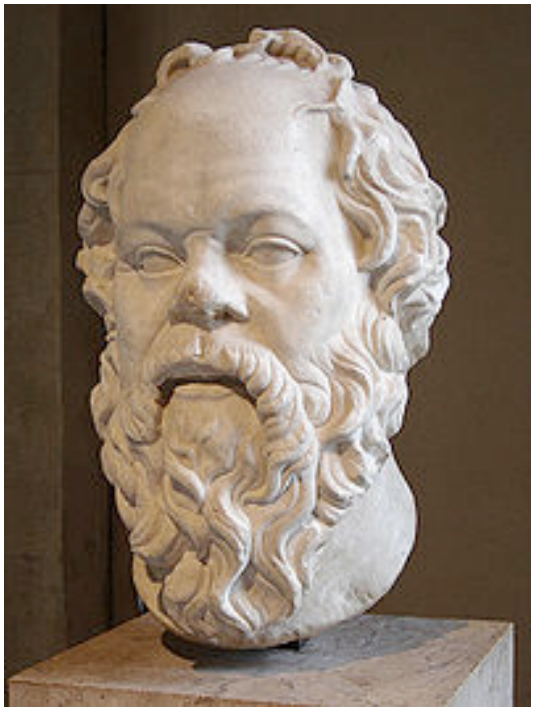
**Duality:**

**$g^2 N$ small → R small → perturbation theory**

**$g^2 N$ large → R large → classical gravity**



# The metaphor of the cave, 380 B.C.



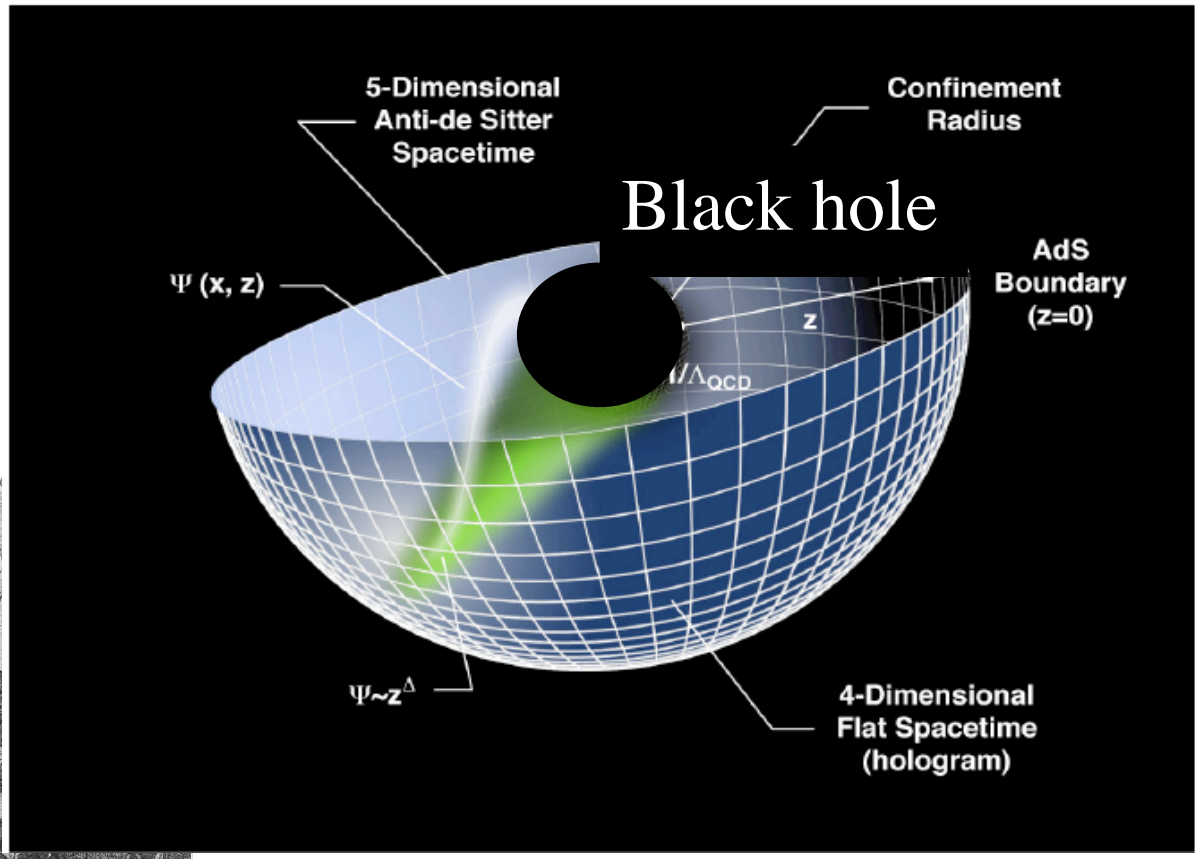
**Socrates (Σωκράτης)**
**469 - 399 B.C.**

"Physical objects and physical events are only "shadows" of their ideal or perfect forms, and exist only to the extent that they instantiate the perfect versions of themselves"

Socrates, in Plato's "Republic"


"The prisoners would take the shadows to be real things and the echoes to be real sounds, not just reflections of reality, since they are all they had ever seen or heard."

# The metaphor of the cave, 2011 A.D.





"The prisoners would take the shadows to be real things and the echoes to be real sounds, not just reflections of reality, since they are all they had ever seen or heard."

# The successes

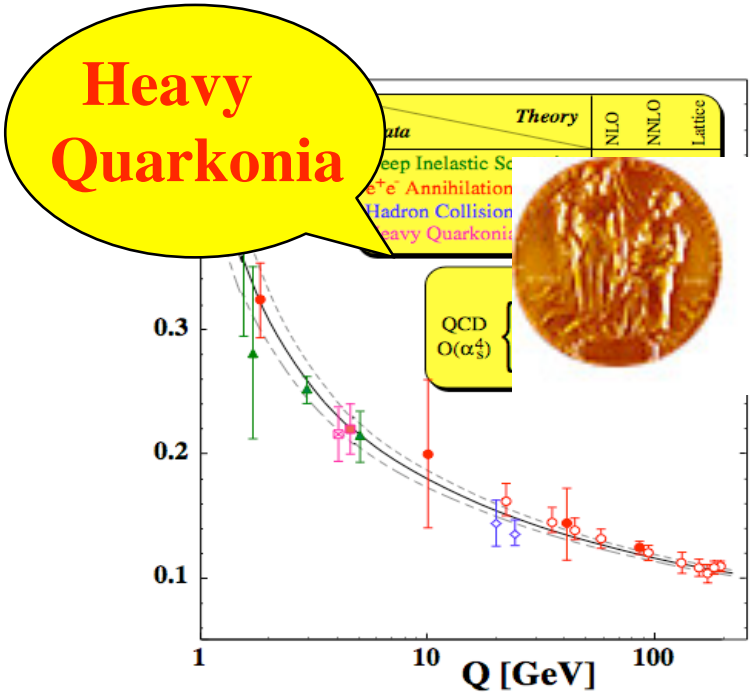
## QCD = quarks + geometry

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}^a_f (i\gamma_\mu D_\mu - m_f) q^a_f;$$

$$D_\mu = \partial_\mu - igA^a_\mu t^a$$

**Elegant, consistent, and correct theory**

# Asymptotic Freedom: "atoms" revealed




At short distances,
the strong force becomes weak
(anti-screening) -
one can access the "asymptotically free" regime in hard processes

Text

and in super-dense matter
(inter-particle distances ~ 1/T)

$$\alpha_s(Q) \simeq \frac{4\pi}{b \ln(Q^2/\Lambda^2)}$$

number of colors

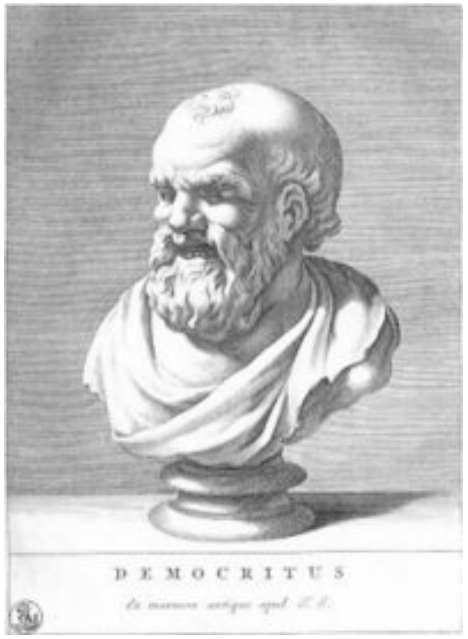
number of flavors

$$b = (11N_c - 2N_f)/3$$

But: Strong confining interaction at large distances

# Where do we stand? (V B.C.)

- "Atoms"
- Geometry
- Void




# Where do we stand? (2010 A.D.)

- [x] "Atoms" identified: quarks and leptons
- [ ] Geometry (gauge field dynamics)
- [ ] Void (the structure of the vacuum)

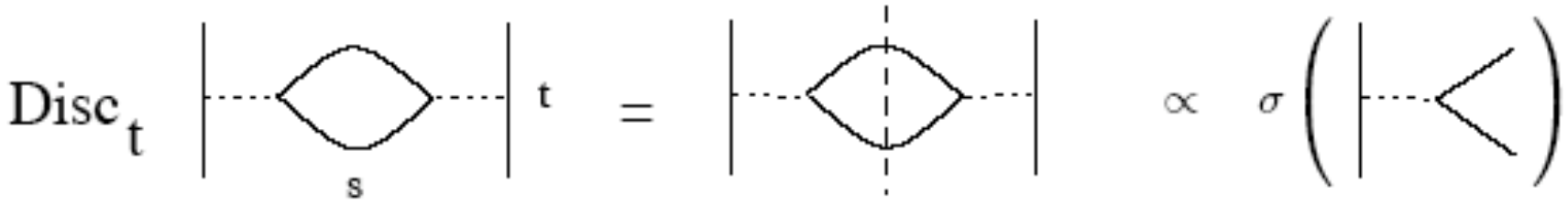
The next step:
from particles ("atoms") to fields (geometry)

# QCD: understanding the dynamics of gauge fields (geometry)

| Problem | | Measurement |
|---|---|---|
| Weak/vacuum fields | ↔ | Jets, parton fragmentation |
| Strong static fields | ↔ | Small x distributions in nuclei |
| Real-time dynamics | ↔ | EM probes, jets, quarkonia |
| Gauge fields with boundary conditions/ event horizons | ↔ | Bulk behavior, quarkonia, soft photons and dileptons, ... |
| Low-energy effective Theory of Everything: hydrodynamics | ↔ | Transport properties: shear and bulk viscosities, vorticity |
| Topology of gauge fields | ↔ | Local parity violation, spin |

# Quarkonium and asymptotic freedom (Coulomb potential)

Spectral representation in the t-channel: $V(R) = \sum_m \sigma(m^2)\ \dfrac{\exp(-mR)}{R}$




If physical particles can be produced (positive spectral density), then unitarity implies <u>screening</u>

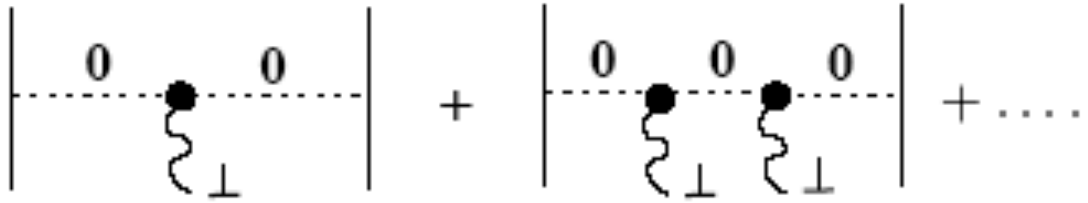
$$\left\{\frac{d\,\alpha_s^{-1}(R)}{d\ln R}\right\}^{\text{phys}} \propto \frac{1}{3}N + \frac{2}{3}n_f$$

Gluons (transverse) Quarks

# Coulomb potential in QCD - II

Missing non-Abelian effect: instantaneous Coulomb exchange dressed by (zero modes of) transverse gluons

$$\sum_n \left[0 + \perp \to 0\right]^n \quad = \quad$$



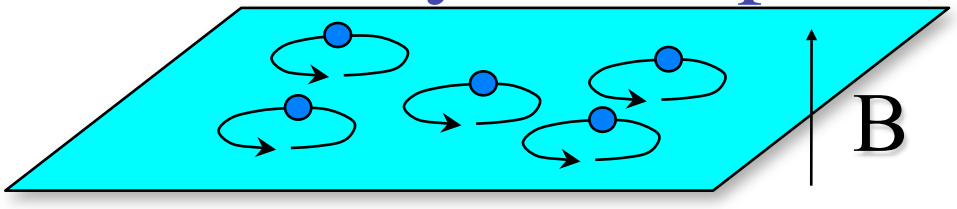

Negative sign
(the shift of the ground level
due to perturbations - unstable vacuum! ):

$$\delta E \equiv E - E_0 = \sum_n \frac{|\langle 0|\delta V|n\rangle|^2}{E_0 - E_n} \; < \; 0$$

Anti-screening

$$\left\{\frac{d\,\alpha_s^{-1}(R)}{d\ln R}\right\}^{\text{stat}} \propto -4N$$

# Asymptotic freedom and the instability of the perturbative vacuum

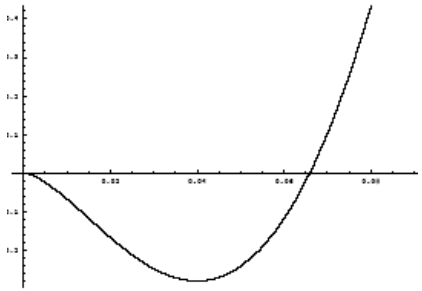



The effective potential: sum over 2D Landau levels

$$V_{\rm pert}(H) = \frac{g\,H}{4\,\pi^2}\int dp_z \sum_{n=0}^{\infty}\sum_{s_z=\pm 1}\sqrt{2\,g\,H\,(n+1/2-s_z)+p_z^2}.$$

Paramagnetic response of the vacuum:

$$\mathrm{Re}\,V_{\rm pert}(H) = \frac{1}{2}\,H^2 + (g\,H)^2\,\frac{b}{32\,\pi^2}\left(\ln\frac{g\,H}{\mu^2} - \frac{1}{2}\right)$$




1. The lowest level n=0 of radius $\sim (gH)^{-1/2}$ is unstable!

2. Strong fields ⟷ Short distances

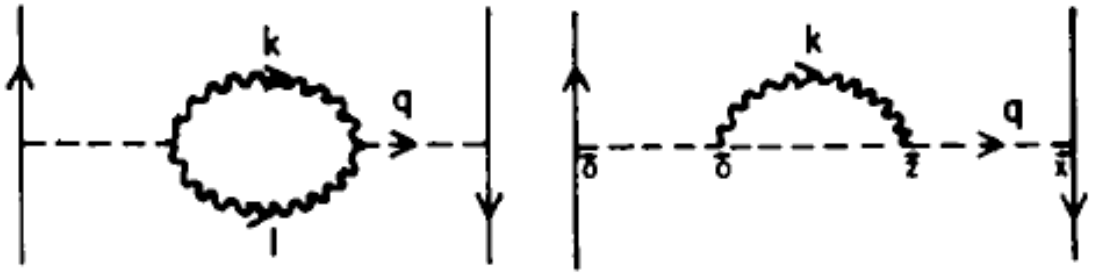
Instability of perturbative QCD vacuum; What is the true ground state?

# Quarkonia: the potential problems...

$$D^{ab}_{\mu\nu} = i\,\delta^{ab}\frac{1}{\vec{k}^2} \qquad \mu = \nu = 0$$

Coulomb gauge

$$= i\,\delta^{ab}\left(\delta_{ij} - \frac{k_i k_j}{\vec{k}^2}\right)\frac{1}{k^2 + i\epsilon} \qquad \mu = i,\ \nu = j.$$




Screening Anti-Screening

**THE STATIC POTENTIAL IN QUANTUM CHROMODYNAMICS**

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Received 18 May 1977

# Quarkonia: the potential problems...

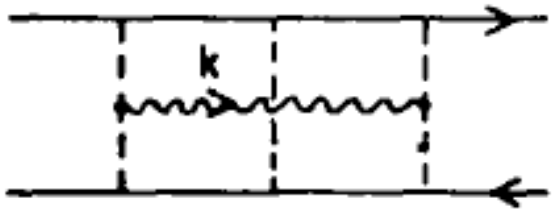
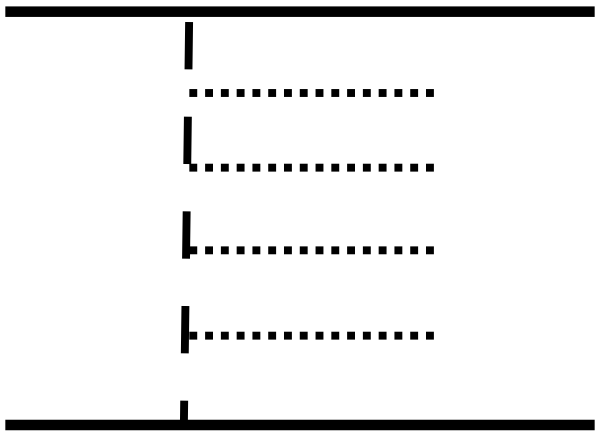



Fig. 4. A three loop graph with a singular static limit.

Higher Fock states; classified in NRQCD Bodwin, Braaten, Lepage; ...



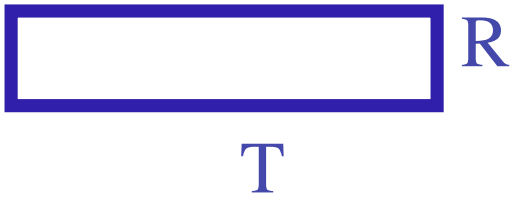
energy of transverse gluons - constant per unit of length (planar, large N limit); ... a string?

e.g., the "gluon chain" model Greensite and Thorn

... can be seen as parts of the QCD string?

# Scale invariance and confinement

Consider a rectangular Wilson loop:




$$W(C) = \exp\left(ig \int_C A_\mu dx^\mu\right)$$

It is related to the potential $V(R)$ acting between the charges $Q$ and $\bar{Q}$:

$$W(C) \to \exp\left(-TV(R)\right)$$

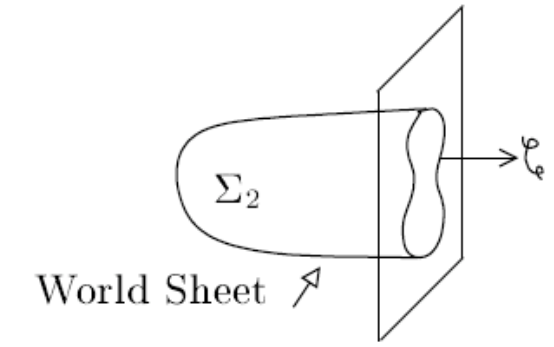
Scale transformation: $T \to \lambda T$; $R \to \lambda R$;

the only solution: Coulomb potential

$$V(R) \sim \frac{1}{R}$$

# Insights from holography

$$V(L) = -\lim_{T\to\infty} \frac{1}{T} \ln \langle W(C_{L\times T})\rangle \, .$$




Of course, no confinement in N=4 SYM: scale invariance dictates that the expectation value of W must scale with T/L - thus Coulomb potential

$$V(L) \sim 1/L$$

Nevertheless, an interesting lesson: solving for the minimal surface in super-gravity and evaluating its area, one finds

$$V(L) = -\frac{4\pi^2\sqrt{\lambda}}{\Gamma^4(1/4)\, L}.$$

$$N \to \infty, \quad \lambda = g^2_{YM} N$$

Why square root?
"not your grandfather's Coulomb potential",
a weaker one! screening?

# Insights from holography

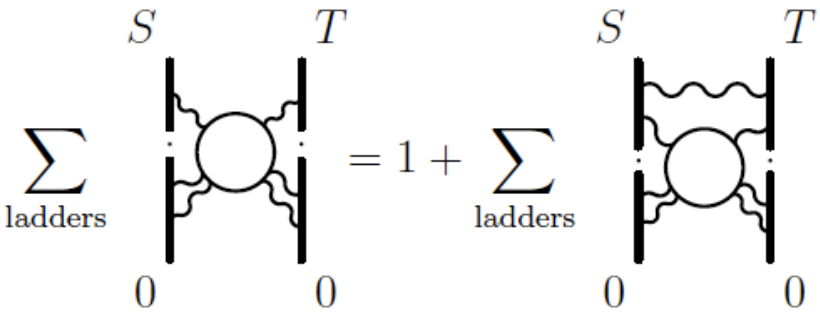
$$\alpha(\lambda) = \begin{cases} \dfrac{\lambda}{4\pi} + \cdots, & \text{for } \lambda \to 0; \\ \dfrac{4\pi^2\sqrt{2\lambda}}{\Gamma^4(1/4)} + O(1), & \text{for } \lambda \to \infty. \end{cases}$$

$$V(L) = -\frac{\alpha(L)}{L}$$

Indeed, the square root of the coupling (but not the pre-factor) can be reproduced on the Field Theory side by resummation of planar diagrams:

Erickson, Semenoff Szabo, Zarembo, hep-th/9911088

$$-\ln\left\{1 + \quad + \quad + \cdots\right\} = \frac{\lambda}{4\pi}\frac{T}{L} - \frac{\lambda^2}{(2\pi)^3}\frac{T}{L}\ln\frac{T}{L} + \cdots .$$




$$\alpha(\lambda) = \frac{\sqrt{\lambda}}{\pi} - 1 + O(1/\sqrt{\lambda}),$$

Infinite number of higher Fock states, but their effect may be resummed?

# J/Ψ as a probe of QGP

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

## J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

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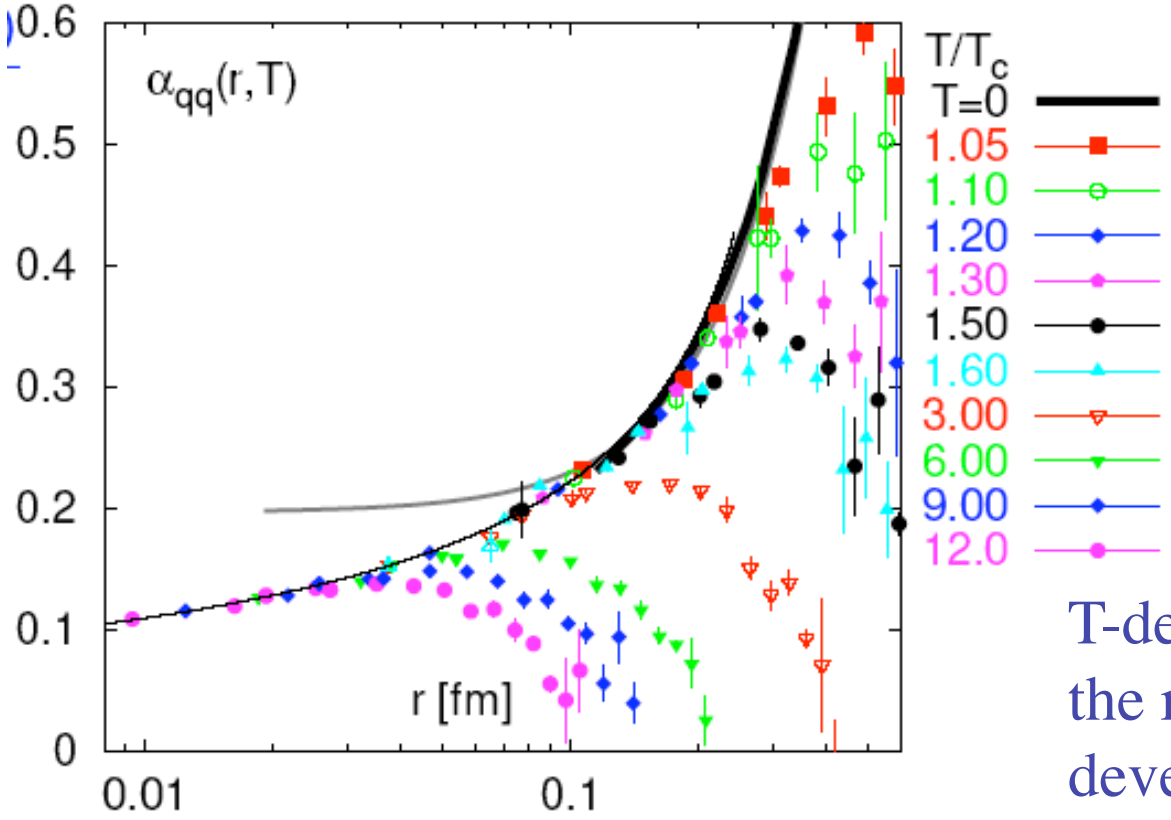
Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

# Screening in QGP



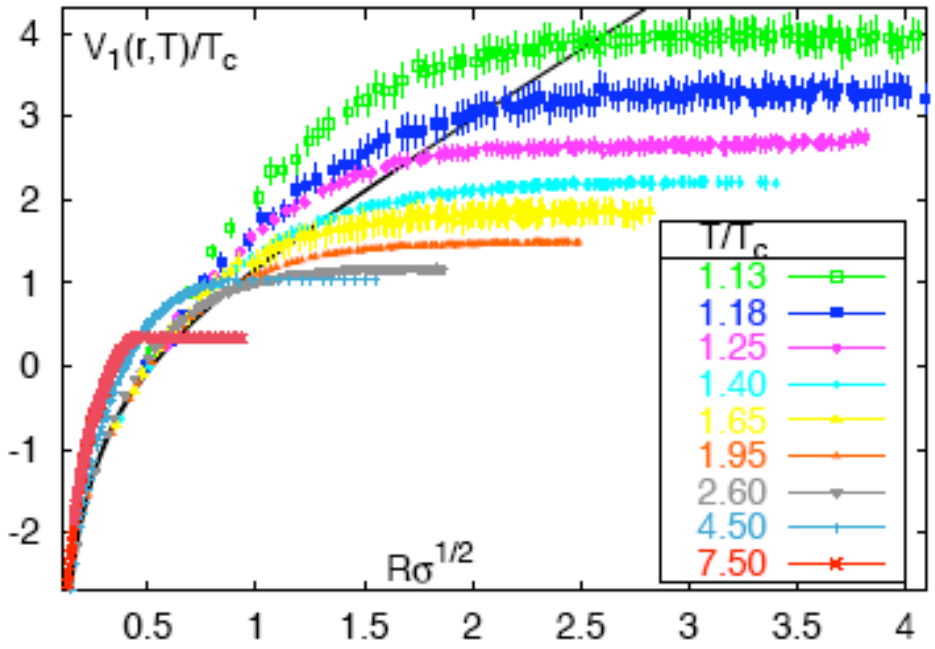

Strong force is screened by the presence of thermal gluons and quarks

T-dependence of the running coupling develops in the non-perturbative region at $T < 3\ T_c$ ; $\Delta E/T > 1$

- "cold" plasma

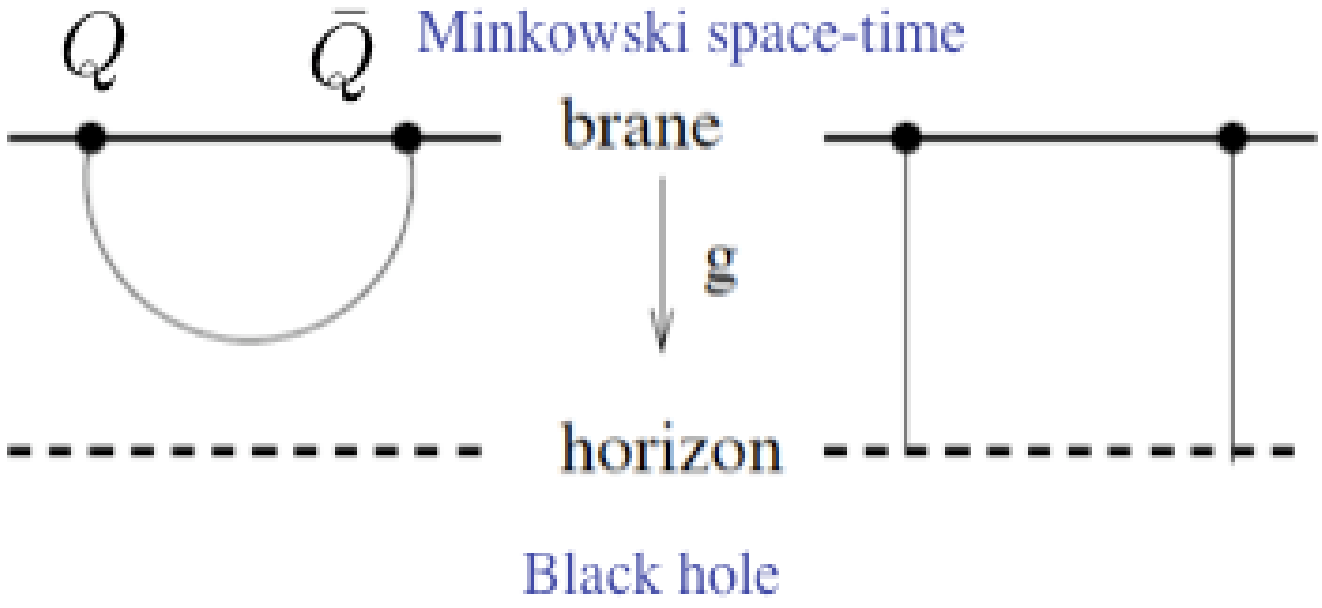
O.Kaczmarek, F. Karsch, P.Petreczky, F. Zantow, hep-lat/0309121

# Heavy quark internal energy above T




O.Kaczmarek, F. Karsch, P.Petreczky,
F. Zantow, hep-lat/0309121

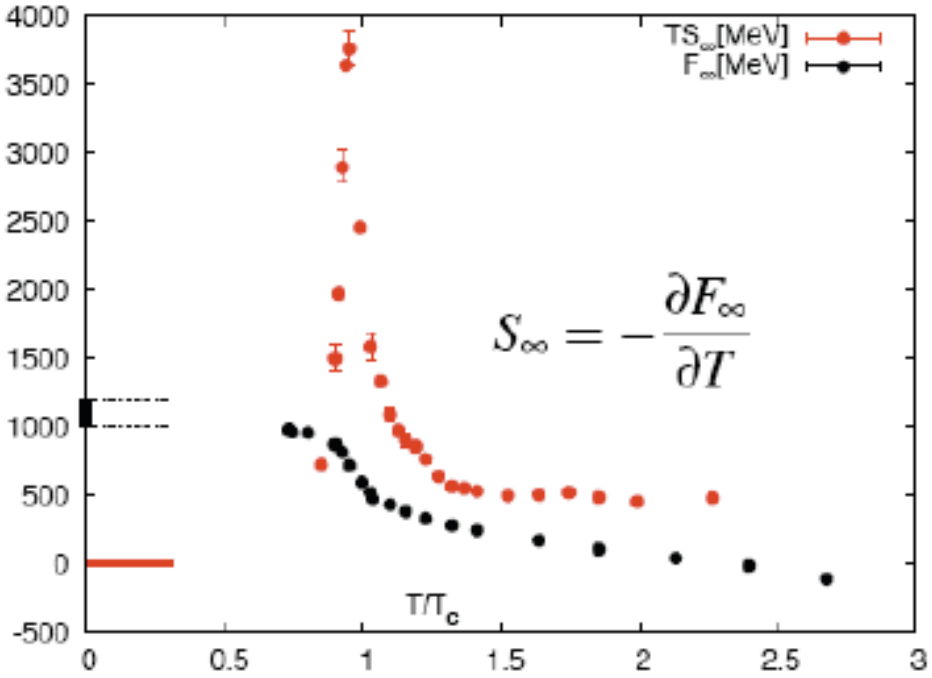
# Color screening and black holes




What is the effect
on the entropy?

Shuryak and Zahed,
hep-th/0308073

Entropy: coupling to real states =>
non-instantaneous, non-local effective potential

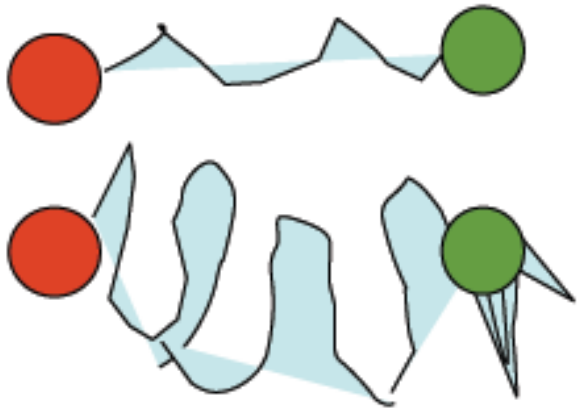



String contribution to
the black hole entropy:
a hint for understanding
better quarkonia
in the QCD plasma?

$$F = U - TS$$

$$\delta F = (\frac{\partial U}{\partial l} - T\frac{\partial S}{\partial l})\ \delta l = 0$$

Kosterlitz-Thouless phase transition:
Frautschi, Polyakov



# Summary

**QCD is a fundamental theory responsible for 95% of the mass of the visible Universe**

**Heavy quarkonium has been, and remains to be, an important testing ground for new approaches to QCD, such as gauge/gravity**

**New data (LHC, RHIC, ...) appear and drive the development of theory**