# *Partons and mesons in a strongly coupled plasma from AdS/CFT*

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# Introduction

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  - "strongly coupled quark–gluon plasma (sQGP)"

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- How to perform calculations at strong coupling ?
  - lattice QCD: first–principle method ... but only for static quantities (thermodynamics, screening masses)
  - $\mathcal{N} = 4$ supersymmetric Yang–Mills (SYM) theory: string theory techniques via the AdS/CFT duality

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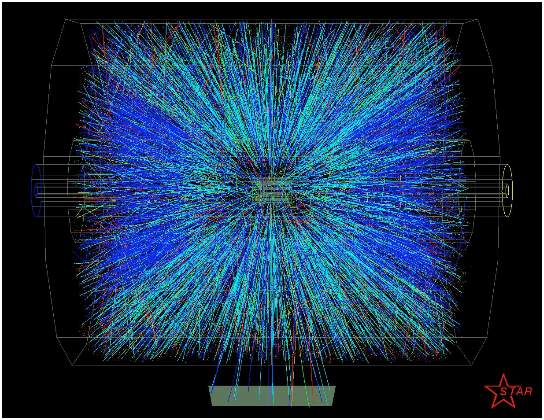
- How to perform calculations at strong coupling ?
  - lattice QCD: first–principle method ... but only for static quantities (thermodynamics, screening masses)
  - $\mathcal{N} = 4$ supersymmetric Yang–Mills (SYM) theory: string theory techniques via the AdS/CFT duality
- Can we trust AdS/CFT in relation with QCD ?
  - for qualitative understanding at most (still interesting !)
  - for specific observables & phenomena

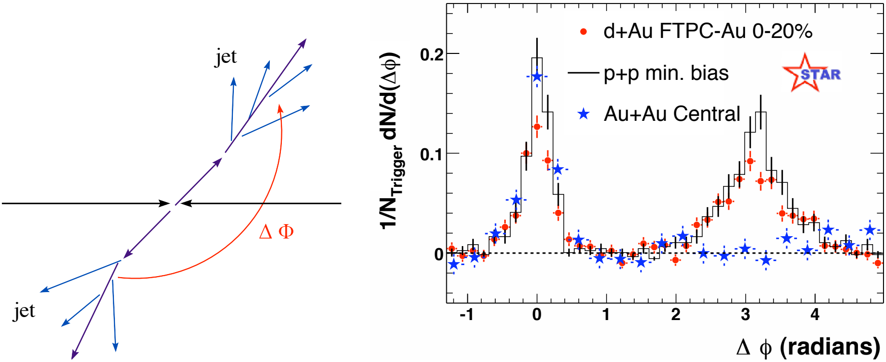
# Motivations: Heavy Ion Collisions @ RHIC & LHC


# Hadron production at RHIC




- $\sim$ 3000 hadrons in the final state
- Particle correlations are essential to disentangle phenomena

# Jets in proton–proton collisions

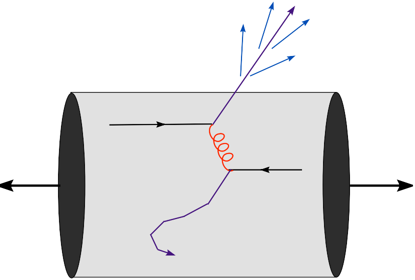


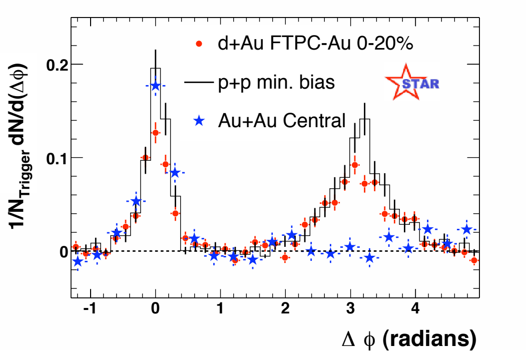

[Nucl.Phys.A783:249-260,2007]

- Azimuthal correlations between the produced jets:

p+p or d+Au : a peak at $\Delta\Phi = 180^{\circ}$

# Jet 'quenching' in nucleus–nucleus collisions

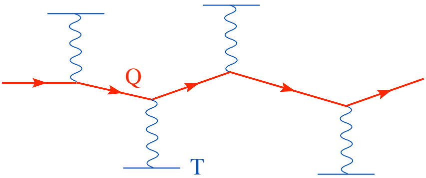





- The "away–side" jet has disappeared (for relatively hard momenta: $Q \sim 2 \div 10$ GeV $\gg$ $T \simeq 400$ MeV)
  $\Longrightarrow$ strong interactions in the medium
- Perturbation theory seems unable to explain this suppression

# Jet quenching in perturbative QCD

- Medium rescattering $\Longrightarrow$ transverse momentum broadening




$$\frac{\mathrm{d}\langle k_\perp^2 \rangle}{\mathrm{d}t} \equiv \hat{q} \simeq \alpha_s N_c\, \mathcal{G}(x, Q^2)$$

- $\mathcal{G}(x, Q^2)$ : gluon distribution per unit volume in the medium

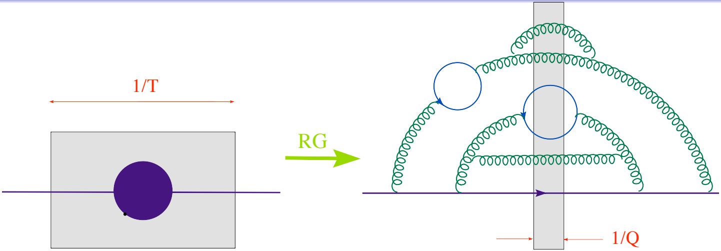
  on the resolution scales $Q^2 \sim \langle k_\perp^2 \rangle$ and $1/x \sim k_z T/Q^2$

- If "medium" = QCD plasma at temperature $T$:

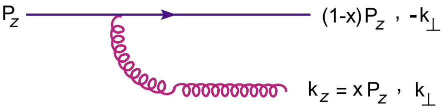
  we expect quarks and gluons with momenta $\sim T$

- Jet quenching requires parton evolution from $T$ up to $Q \gg T$

# Parton evolution




- A 'quasiparticle' (quark or gluon) on the scale $T$ may reveal itself as highly composite on the harder scale $Q \gg T$
- Weak coupling: Bremsstrahlung




$$\mathrm{d}\mathcal{P}_{\rm Brem} \sim \alpha_s N_c \frac{\mathrm{d}^2 k_\perp}{k_\perp^2} \frac{\mathrm{d}x}{x}$$

soft ($x \ll 1$) & collinear ($k_\perp \to 0$)

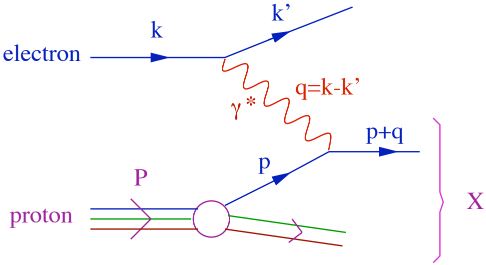
# Deep inelastic scattering

- How to study parton evolution at strong coupling ?
- DIS: a non–perturbative & observable definition of 'partons'

- 2 independent variables:

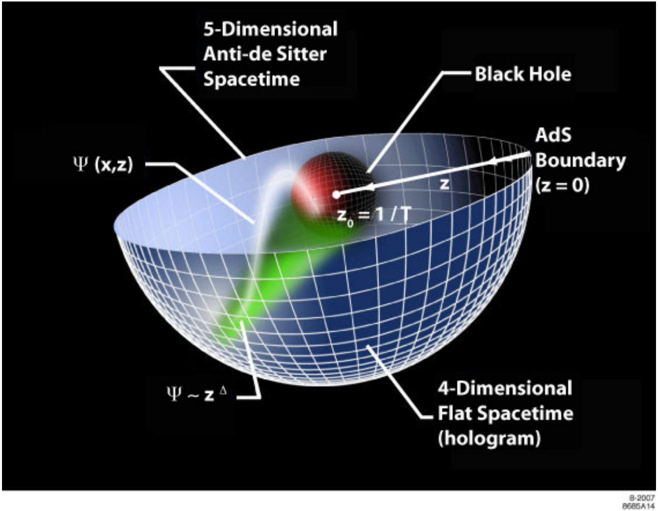
$$Q^2 \equiv -q^\mu q_\mu \geq 0$$

$$x \equiv \frac{Q^2}{2P \cdot q}$$




- Physical picture: $\gamma^*$ absorbed by a quark excitation with
  - transverse size $\Delta x_\perp \sim 1/Q$
  - and longitudinal momentum $p_z = xP$
- DIS 'structure function' $F_2(x, Q^2)$: quark distribution

# Parton evolution at strong coupling

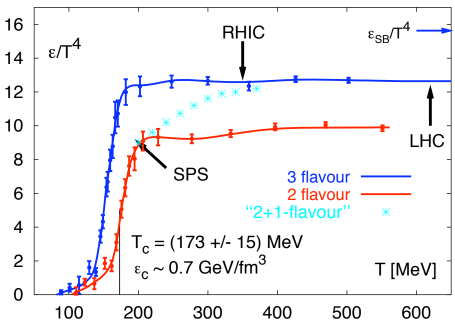


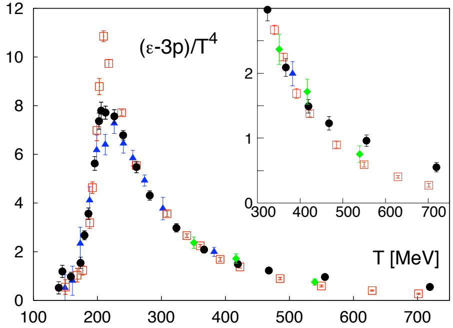

*(courtesy of Stan Brodsky and MM)*

# The AdS/CFT correspondance *(Maldacena, 1997)*

- A 'duality' (equivalence) between two very different theories
- Gauge theory in $D = 4$: $\mathcal{N} = 4$ Supersymmetric Yang–Mills
  - color gauge group SU($N_c$)
  - conformal invariance, fixed coupling g, no confinement
  - strong 't Hooft coupling : $\lambda \equiv g^2 N_c \gg 1$ & $g^2 \ll 1$
- Is this a good model for QCD ??
- Perhaps better suited for studies of QCD at finite temperature
  - deconfined phase (quark–gluon plasma)
  - nearly conformal for $T \gtrsim 2T_c$
  - coupling is relatively strong in the relevant range

# 'Trace anomaly' in lattice QCD




$$\beta(g)\,\frac{\mathrm{d}p}{\mathrm{d}g} = \langle T^{\mu}_{\mu} \rangle = \mathcal{E} - 3p$$

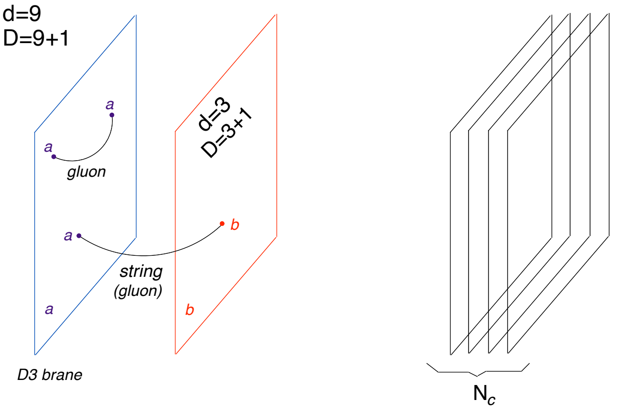
- $(\mathcal{E} - 3p)/\mathcal{E}_0 \lesssim 10\%$ for any $T \gtrsim 2T_c \simeq 400$ MeV
- $g \approx 1.5 \div 2 \implies \lambda \equiv g^2 N_c \simeq 6 \div 10$

# The AdS/CFT correspondance (Maldacena, 1997)

- The $\mathcal{N} = 4$ SYM gauge theory in $D = 3 + 1$ is dual to type IIB string theory in $D = 9 + 1$ ($AdS_5 \times S^5$ space–time)
- The strong 't Hooft coupling regime of the gauge theory:
  - $\lambda \equiv g^2 N_c \gg 1$ & $g^2 \ll 1$ (large $N_c$)
- ... corresponds to the semi–classical regime of the string theory
  - weak coupling & weak curvature
  - string theory reduces to 'supergravity' : classical equations of motion in a curved space–time
- The gauge theory emerges as the low–energy limit of a string theory with $N_c$ 'D3–branes'
- A 'D3–brane': a manifold with D=3+1 immersed into D=9+1

# The AdS/CFT correspondance

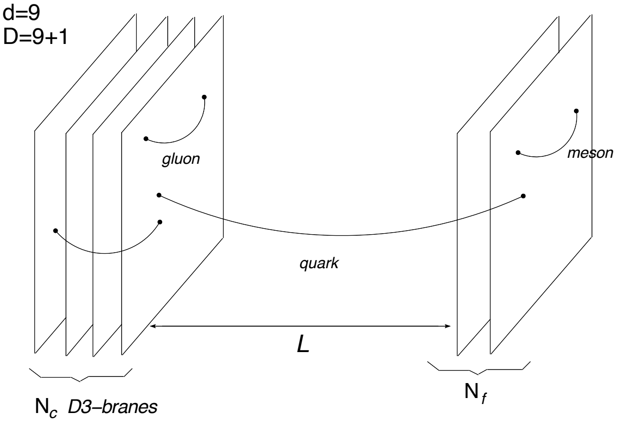
- 'gluons' = strings connecting $N_c$ overlapping D3–branes




- Gluons are massless since the minimal string length is zero

# The AdS/CFT correspondance

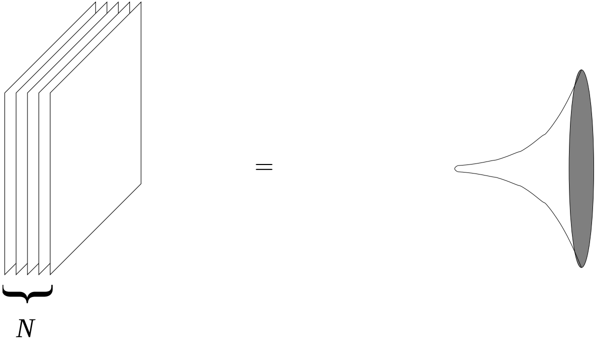
- 'quarks' = strings connecting one of the $N_f$ 'flavor' branes to one of the $N_c$ 'color' branes




- Minimal string length is $L \Longrightarrow$ quark mass $M_q = L \times \mathcal{T}$

# The AdS/CFT correspondance

- The branes are massive $\Longrightarrow$ they deform the space–time




- AdS$_5$ : Our Minkowski world $\times$ a 'radial' dimension $\chi$
  - $0 \leq \chi < \infty$ : 'radial', or '5th', coordinate
  - gauge theory lives at the Minkowski boundary $\chi = 0$

# Heating $AdS_5$ : the Black Hole

- $\mathcal{N}=4$ SYM at finite temperature $\Longleftrightarrow$ Black Hole in $AdS_5$

  A Black Hole has entropy and thermal (Hawking) radiation

- Gauge theory operator $\mathcal{O}(t,\vec{x})$ on the 'boundary' $(\chi=0)$ :

  source for gravity fields $\phi(t,\vec{x},\chi)$ inside the 'bulk' $(\chi>0)$

- Classical EOM for $\phi(t,\vec{x},\chi)$ into $AdS_5 \Longrightarrow$

  quantum correlations for $\mathcal{O}(t,\vec{x})$ in the limit $\lambda\to\infty$

- Absorbtion of the field $\phi(t,\vec{x},\chi)$ by the BH $\Longrightarrow$

  dissipative phenomena within the strongly–coupled plasma

- What is the rôle of the 5th dimension ?

  dual to the 'loop' momenta in the usual Feynman graphs

# DIS off the Black Hole *(Hatta, E.I., Mueller, 07)*

- E.m. current $J^\mu$ in 4D $\longleftrightarrow$ Maxwell wave $A_\mu$ in $AdS_5$ BH
- DIS cross section $\longleftrightarrow$ absorption of the wave by BH

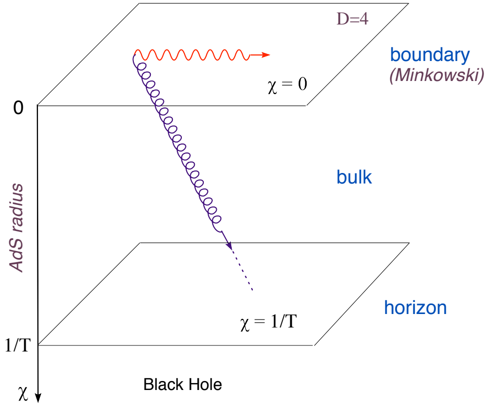
- Physical world: $\chi = 0$

  Black Hole horizon: $\chi = 1/T$
- Maxwell equations in $AdS_5$ BH

$$\partial_m\left(\sqrt{-g}\, g^{mn} g^{pq} F_{nq}\right) = 0$$

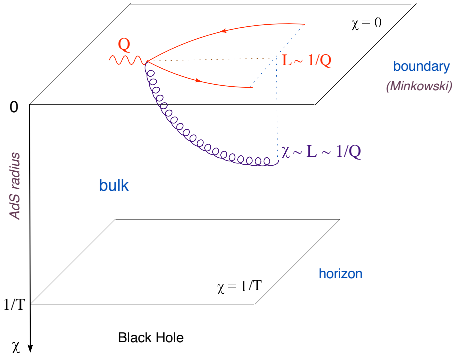
$$F_{mn} = \partial_m A_n - \partial_n A_m$$

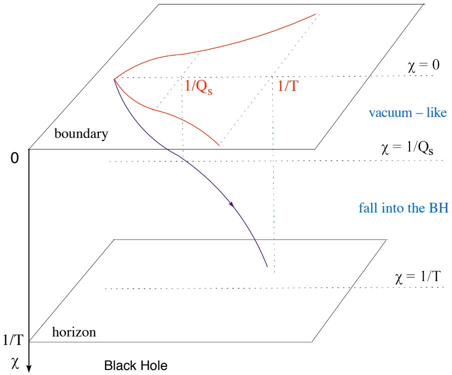
- No explicit coupling



# Space–like photon in the plasma

- Interactions are controlled by the kinematics $(x, Q^2)$
- For low energies, the virtual photon does not 'see' the BH !




- … while for large enough energies, it is completely absorbed !

# Saturation line

- Gravitational interactions are proportional to the energy density in the wave ($\omega$) and in the plasma ($T$)

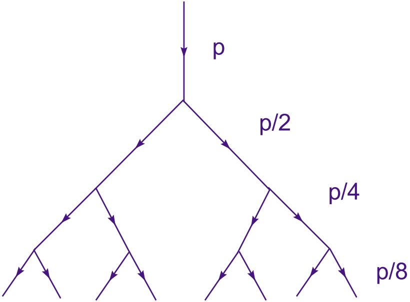
$$\text{DIS kinematics :} \quad x \equiv \frac{Q^2}{2\omega T} \quad \text{and} \quad Q \gg T$$

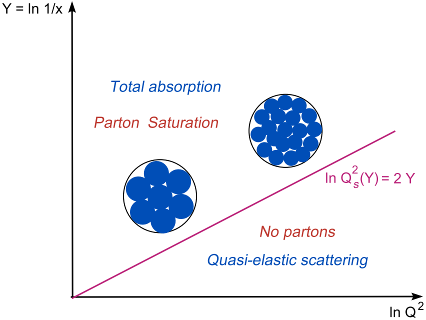
- Large $\omega T$ is tantamount to small Bjorken's $x$
- Critical ('saturation') value $x_s(Q) \simeq \frac{T}{Q} \ll 1$
  - $x > x_s \simeq T/Q$ : $F_2(x, Q^2) \approx 0$ : no partons !
  - $x < x_s \simeq T/Q$ : $F_2(x, Q^2) \sim x N_c^2 Q^2$

  $\Longrightarrow$ Parton saturation with occupation numbers $\mathcal{O}(1)$
- Where did all the partons go ??

# Physical interpretation: Parton evolution

- The energy of the plasma is carried mostly by the partons along the saturation line: $x_s \simeq T/Q \ll 1$

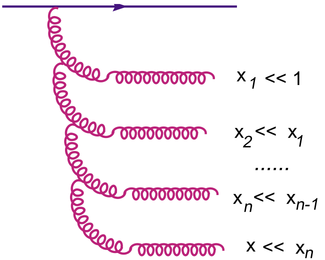



- All partons branch down to the smallest value of $x$ consistent with energy conservation $\Longrightarrow$ no pointlike constituents

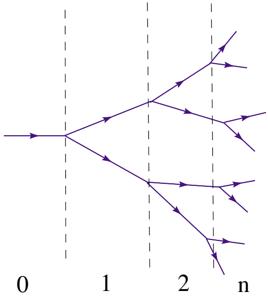
# Parton evolution: weak vs. strong coupling

- Weak coupling




- Bremsstrahlung
- Soft & collinear emissions
- Low multiplicity : $N \propto \ln E$

- Strong coupling



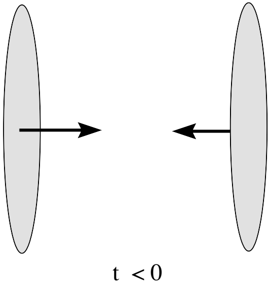

- Quasi–democratic branching :

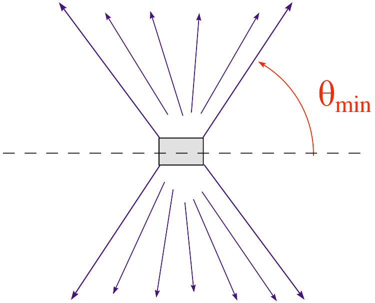
$$\omega_n \sim \omega_{n-1}/2$$

- High multiplicity : $N \propto E/\Lambda$

# No forward/backward jets in $AA$ collisions

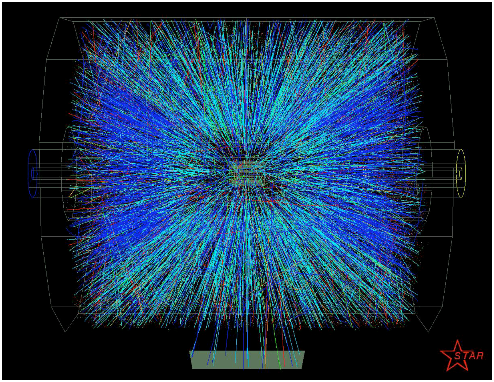
- No large–$x$ partons $\Longrightarrow$ no hard ($Q \gg \Lambda$) particle production at forward/backward rapidities



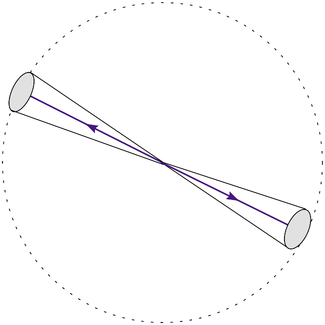

- All the energy is carried out by soft particles with $p \sim \Lambda$

# Partons at RHIC

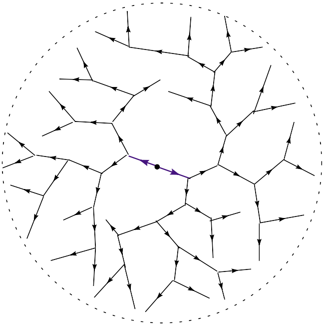



- Partons are actually 'seen' (liberated) in the high energy hadron–hadron collisions
  - central rapidity: small–$x$ partons
  - forward/backward rapidities: large–$x$ partons

# No jets in $e^+e^-$ annihilation !



weak coupling

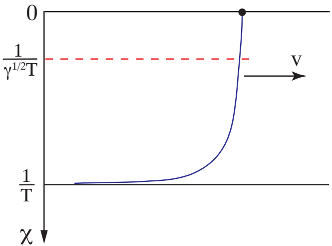


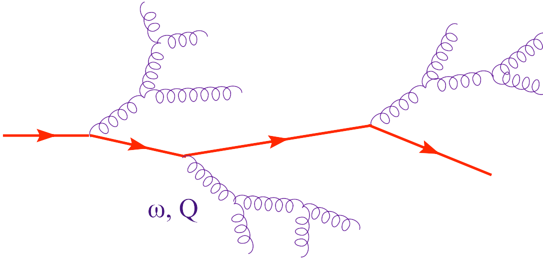
strong coupling

- An isotropic distribution of soft hadrons in the detector

  *(similar conclusions by Hofman and Maldacena, 2008)*

# Heavy Quark in a strongly–coupled plasma




- Medium–induced radiation
  - virtual quanta with $Q \lesssim Q_s$ are liberated into the plasma
  - energy loss, momentum broadening
  - quantum stochasticity (random emissions)

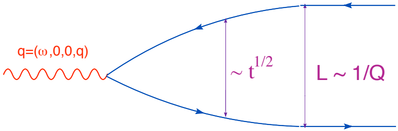
*Casalderrey-Solana and Teaney; Herzog, Karch, Kovtun, Kozcaz, and Yaffe; Gubser, 2006;*

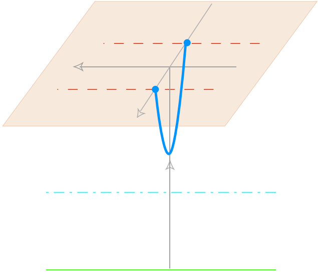
*G. Giecold, E.I., and A. Mueller 2009*

- Different mechanism than in pQCD: radiation vs. rescattering

# Meson dissociation in the plasma

- $q\bar{q}$ fluctuation $\approx$ a 'meson' with transverse size $L \sim 1/Q$



- The 'meson' melts when $L \geq L_s(v)$

$$L_s(v) \sim \frac{1}{Q_s(v)} \sim \frac{(1-v^2)^{1/4}}{T}$$

- Velocity–dependent screening length:
  the faster mesons are easier destroyed in the medium !

*Peeters et al; Liu, Rajagopal, and Wiedemann (2006)*

# AdS/CFT applications to heavy ion collisions

- A very active area of research, with some serious limitations
  - no asymptotic freedom
  - so far, no systematic way to improve
  - high-energy physics looks very different from real–life QCD
- ... but which is still interesting
  - new perspectives on old problems: QGP = Black Hole
  - the potential to solve longstanding puzzles at RHIC (early thermalization, elliptic flow, jet quenching)
  - most likely, the coupling is moderately strong
- It teaches us the unity of physics
  - quantum field theory, nuclear physics, statistical physics, gravity, hydrodynamics ...