



Parton Energy Loss: Perturbative vs Non-Perturbative

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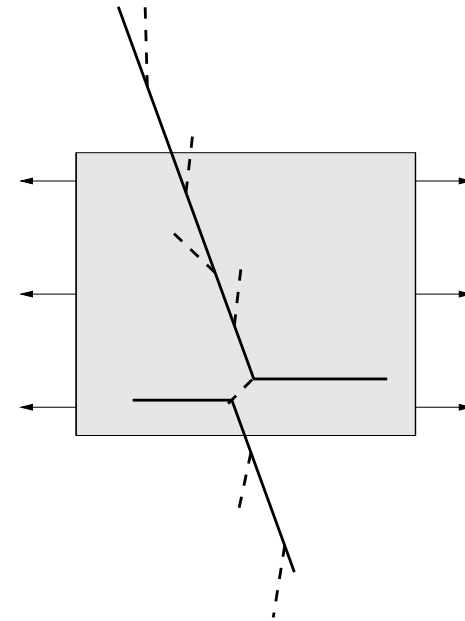
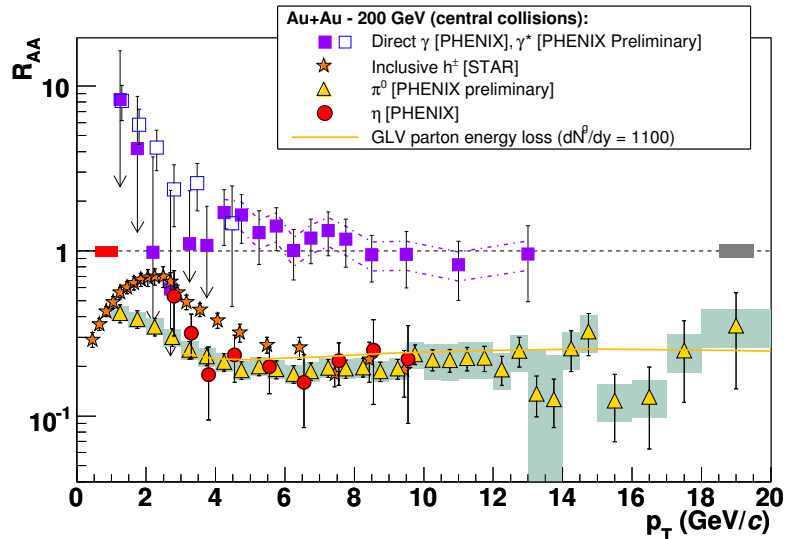
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Rencontres QGP-France 2009 – Etretat

Introduction



good jet-quenching phenomenology requires

accurate theoretical results for ΔE_{parton}





- 1990's: ΔE_{parton} studied by various groups using different methods, but all assuming *perturbative* QGP:

$$g(T) \ll 1 \Leftrightarrow T \gg T_c$$

- \sim 2005: some features of RHIC data have suggested **strongly coupled QGP = sQGP**

$$T_0 \simeq 2T_c \Rightarrow g(T) \gtrsim 1$$

- Since \sim 2000: possible to address (hot) gauge theories **non-perturbatively**, at least

$\mathcal{N} = 4$ Supersymmetric Yang-Mills (SYM),

where **AdS/CFT duality** is expected (Maldacena, 1998)

$\rightarrow \Delta E_{\text{parton}}$ in SYM plasma for $\lambda \gg 1$

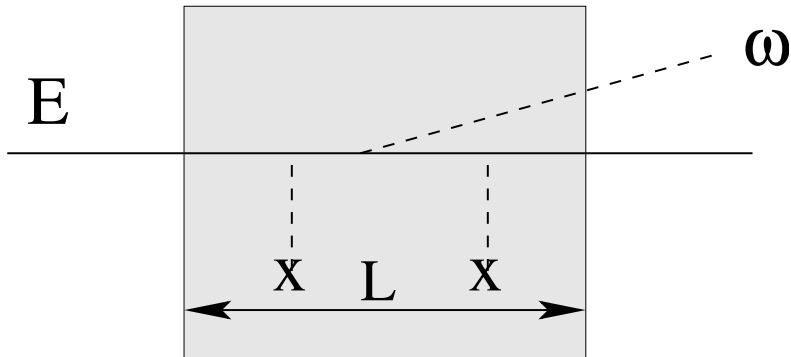


Perturbative ΔE in QCD medium



- QCD medium = QGP or cold nuclear matter
- high energy $\Rightarrow \Delta E \simeq \Delta E_{\text{rad}} \Rightarrow$ two situations:

$$t_{\text{prod}} = -\infty$$

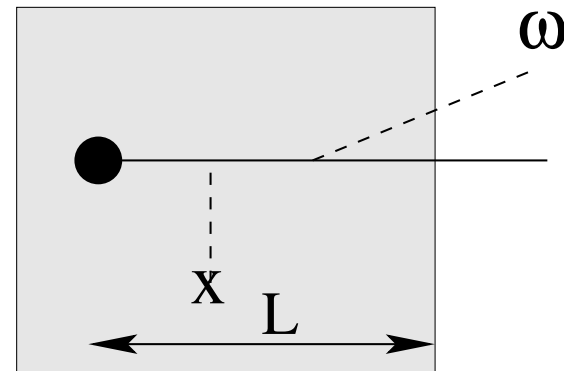


$$\Delta E_{\text{rad}} = \Delta E_{\text{rad}}^{\text{tot}}$$

$$\Delta E_{\text{rad}}(L = 0) = 0$$

(on-shell particle travelling in vacuum does not radiate)

$$t_{\text{prod}} = 0$$



$$\Delta E_{\text{rad}}^{\text{tot}}(L = 0) \neq 0$$

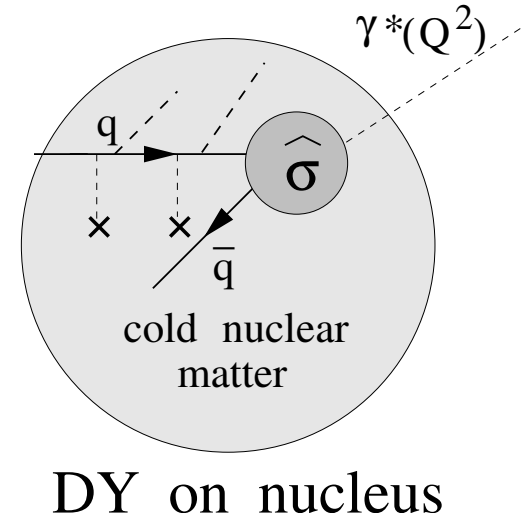
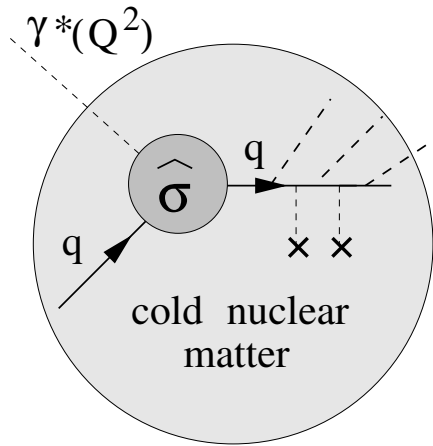
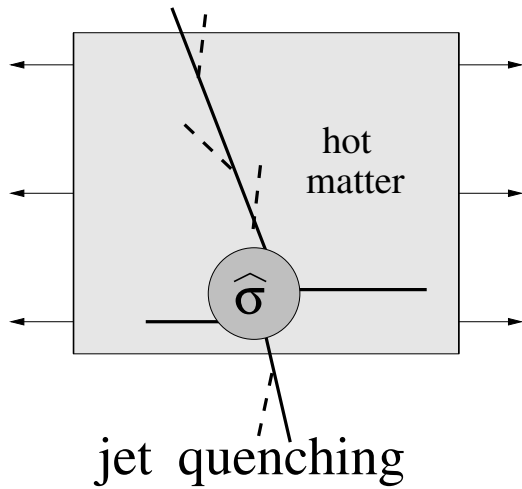
(newly created particle suffers DGLAP radiation)

$$\Delta E_{\text{rad}}^{\text{med}} - \Delta E_{\text{rad}}^{\text{vac}} \equiv \Delta E_{\text{induced}}$$

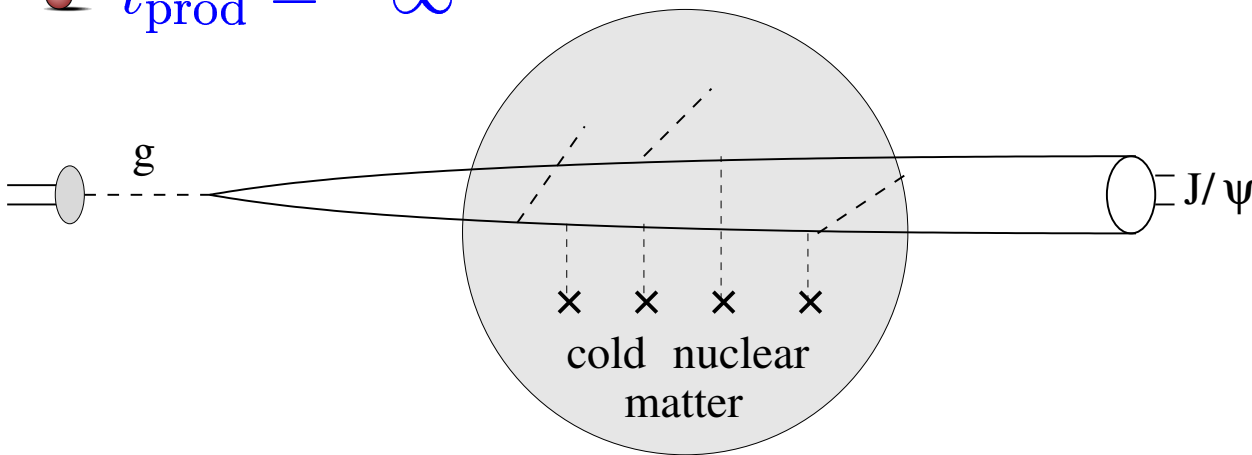




$t_{\text{prod}} = 0$



$t_{\text{prod}} = -\infty$

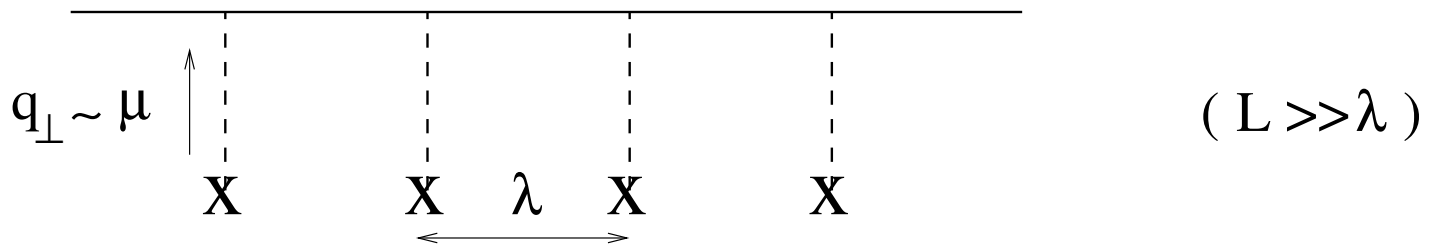


(F. Arleo, S. P.)



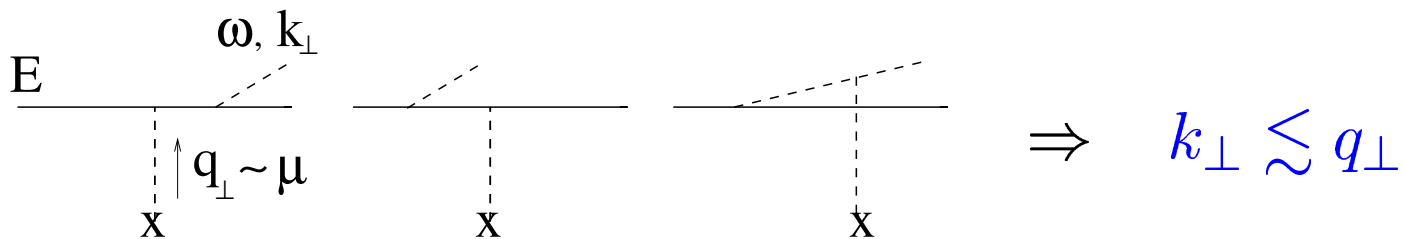
Medium effects on parton propagation

- leading order: elastic scattering



⇒ momentum broadening $\langle \Delta p_{\perp}^2 \rangle_L = \mu^2 \frac{L}{\lambda} = \hat{q}L \quad \hat{q} \equiv \frac{\mu^2}{\lambda}$

- next order: broadening induces radiation



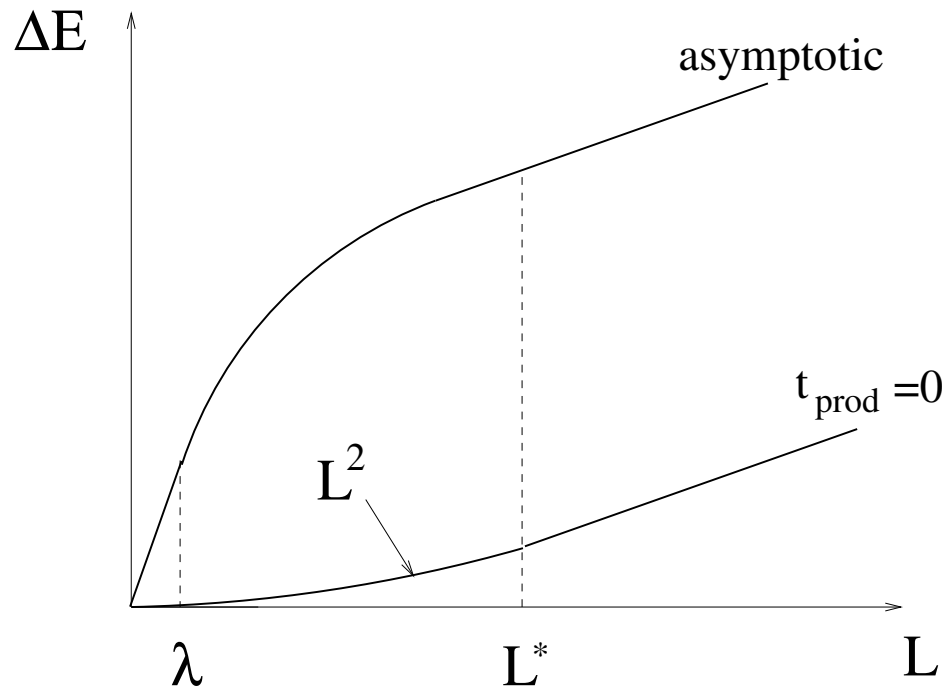
$t_{\text{prod}} = 0:$ $t_f \sim \frac{\omega}{k_{\perp}^2} \lesssim L \Rightarrow \frac{dE}{dx} \sim \frac{\omega}{t_f} \cdot \alpha_s \sim \alpha_s \cdot k_{\perp}^2$

$\frac{dE}{dx} \Big|_{\text{induced}} \sim \alpha_s \cdot q_{\perp}^2(t_f)$



light parton
energy loss

$$L^* = \sqrt{\frac{E}{\hat{q}}}$$



(heavy quark: qualitatively similar, but $L^* \rightarrow \tilde{L}^* = (\frac{E^2}{\hat{q}M^2})^{1/3}$)

- maybe, $\Delta E_{\text{induced}}(L < L^*) \sim \alpha_s \hat{q} L^2$ valid when $\alpha_s \sim 1$, provided $\hat{q} = \hat{q}_{\text{eff}}$??



- **worth trying non-perturbative approach**

don't discard perturbative approach!



- energy loss physics is very rich
 - momentum broadening
 - LPM effect
 - dead cone effect
- PQCD predictive, and predicts much more than ΔE
 - gluon energy spectra
 - k_{\perp} distributions
- PT understanding still improving
 - (Arnold, 0903.1081 [nucl-th])
 - (Aurenche, Zakharov, 0907.1918 [hep-ph])
- perturbative approach justified in cold nuclear matter
 - nuclear DIS at HERMES, CLAS, LHeC



ΔE from AdS/CFT

AdS/CFT correspondence

- context: **Supersymmetric String Theory**

elementary objects = *strings* $\ell_s \sim \ell_{\text{Planck}} = 1.6 \cdot 10^{-35} \text{ m}$

- \exists five consistent SST's (Green & Schwarz, 1985)
 - living in $d = 10$ dimensions
 - related by dualities (Horava & Witten, 1995)

- string theory **includes gravitation**

$$\Rightarrow R_{ab} - \frac{1}{2}g_{ab}R + g_{ab}\Lambda = 0 \Rightarrow R_{ab} \propto g_{ab}$$

spacetime = Einstein manifold

What are the allowed Einstein manifolds to have a consistent theory?

constraint: 4-dim Minkowski spacetime $\mathbb{R}^3 \times \mathbb{R}$ must be a boundary



Hint: Holographic Principle:

a theory containing gravity must be dual to the boundary theory

(full theory in $d = 10$ inferred from $d = 4$ theory!)

- Maldacena conjecture (AdS/CFT correspondence):

$\mathcal{N} = 4$ $SU(N_c)$ SYM
in $d = 4$ Minkowski
spacetime

\Leftrightarrow Type IIB SST on $AdS_5 \times S^5$
 $ds_{AdS}^2 = \frac{r^2}{R^2} (d\vec{x}^2 - dt^2) + \frac{R^2}{r^2} dr^2$

(isometry group of $AdS_5 \times S^5 = SO(2, 4) \times SO(6)$)

- parameters: $g_{YM}^2 = 4\pi g_s$

$$\lambda = g_{YM}^2 N_c = \left(\frac{R}{\ell_s}\right)^4$$

$g_{YM} \rightarrow 0, N_c \rightarrow \infty$
with fixed $\lambda \gg 1$

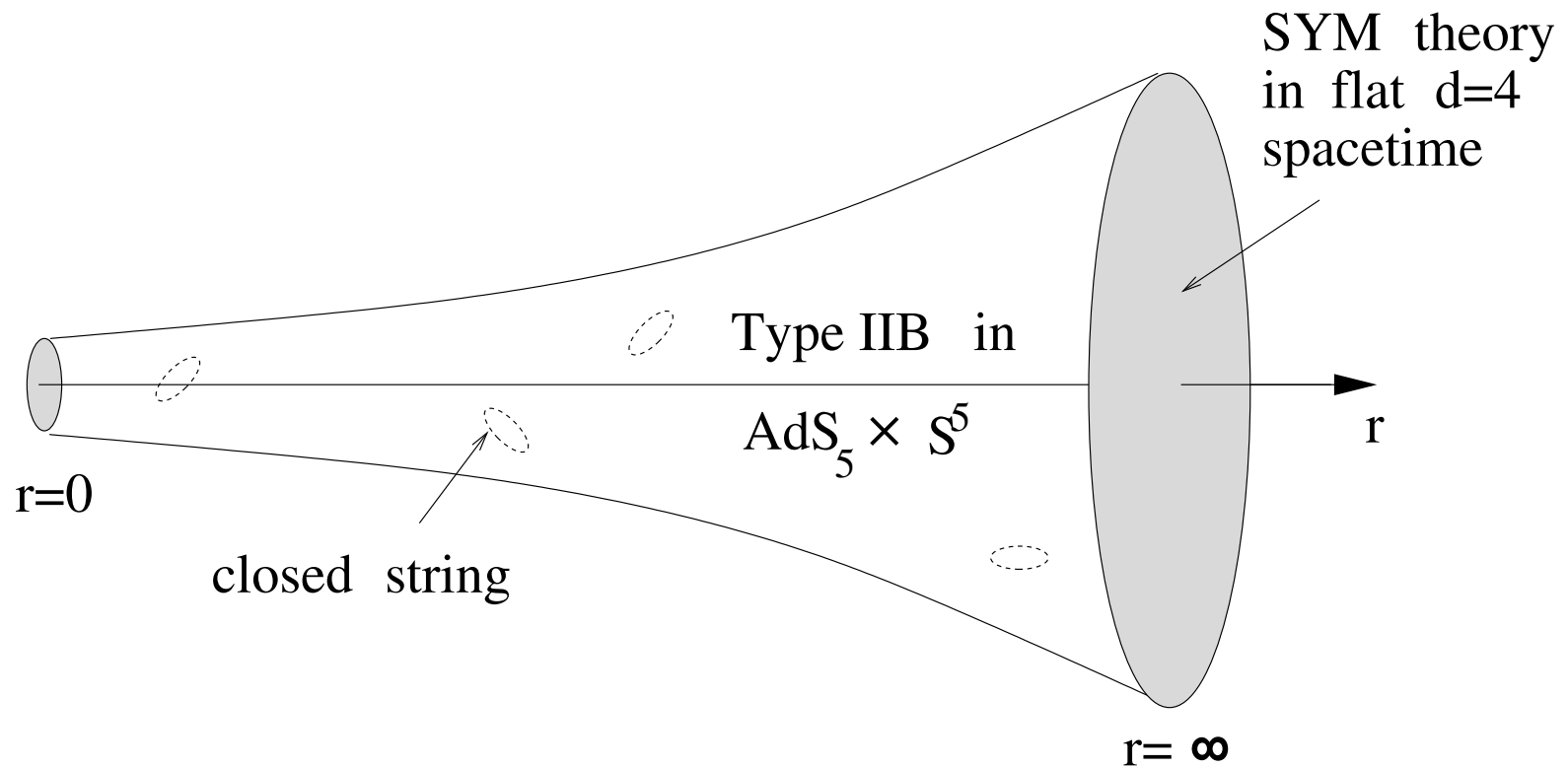
\Leftrightarrow $g_s \ll 1$ (weakly coupled)
 $R \gg \ell_s$ (weakly curved)



NP quantum
calculation in $d = 4$
boundary SYM theory

\Leftrightarrow

classical supergravity
calculation in $AdS_5 \times S^5$



Heavy quark ΔE in SYM plasma

● AdS/CFT at $T \neq 0$: (Witten, 1998)

$T = 0$: SYM on boundary $\mathbb{R}^3 \times \mathbb{R}$

$T \neq 0$: boundary is now $\mathbb{R}^3 \times S^1(\beta)$ ($\beta = 1/T$)

look for Einstein manifold with boundary $\mathbb{R}^3 \times S^1(\beta)$ instead of \mathbb{R}^4

\Rightarrow “AdS - black hole” metric:

$$ds^2|_{AdS-BH} = \frac{r^2}{R^2} (d\vec{x}^2 - f dt^2) + \frac{R^2}{r^2 f} dr^2 \quad ; \quad f = 1 - \frac{r_0^4}{r^4}$$

black hole singularity at the horizon $r = r_0 = \pi R^2 T$

raise temperature T
on boundary

\Leftrightarrow

add black hole located at
 $r = r_0 = \pi R^2 T$ in AdS space

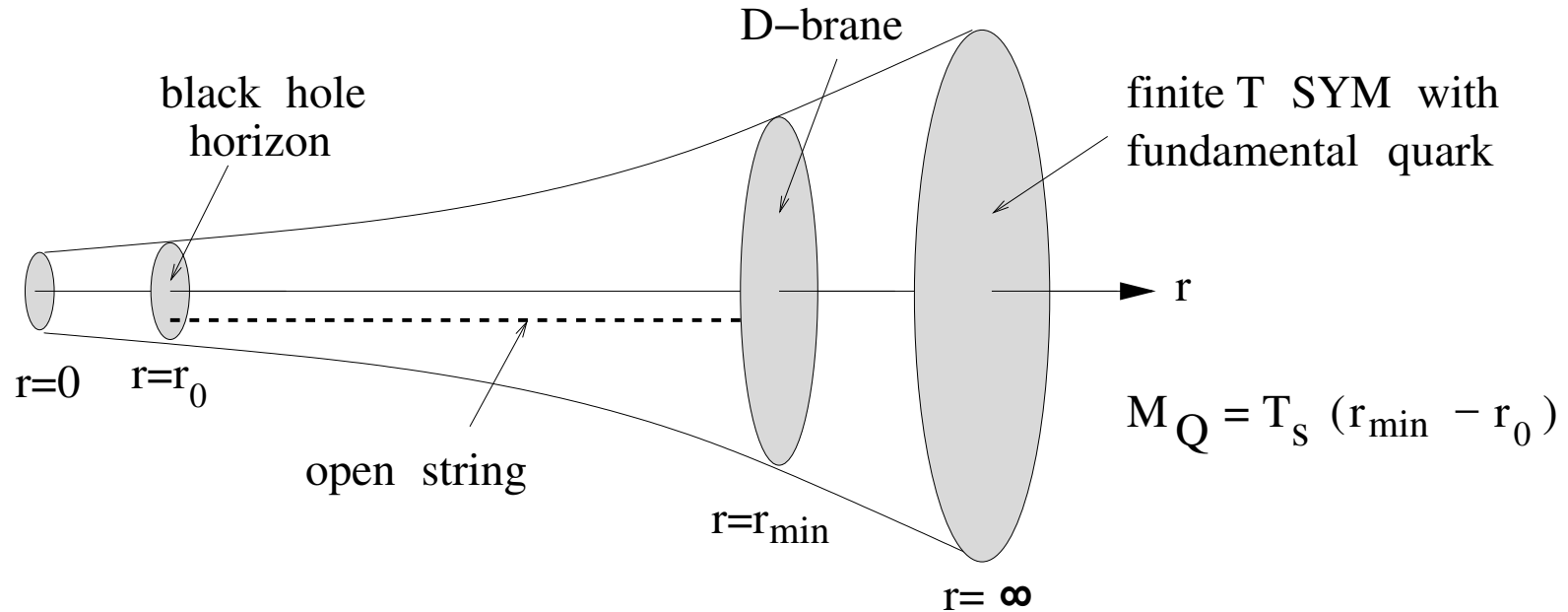


• add quark flavour to the picture (Karch & Katz, 2002)

add fundamental quark
in boundary theory



add D-brane down to
 $r = r_{\min}$ in AdS space



heavy quark moving in
 $\mathcal{N} = 4 SU(N_c)$ SYM plasma



open string endpoint
moving on D-brane





AdS/CFT studies of ΔE_{parton}

Herzog et al, hep-th/0605158

Gubser, hep-th/0605182

Gubser et al, 0803.1470

Hatta, Iancu, Mueller, 0803.2481

Fadafan et al, 0809.2869

Chesler et al, 0810.1985

Marquet, 0810.2572

Giecold, Iancu, Mueller, 0903.1840



The trailing string picture

(Herzog et al, 2006)

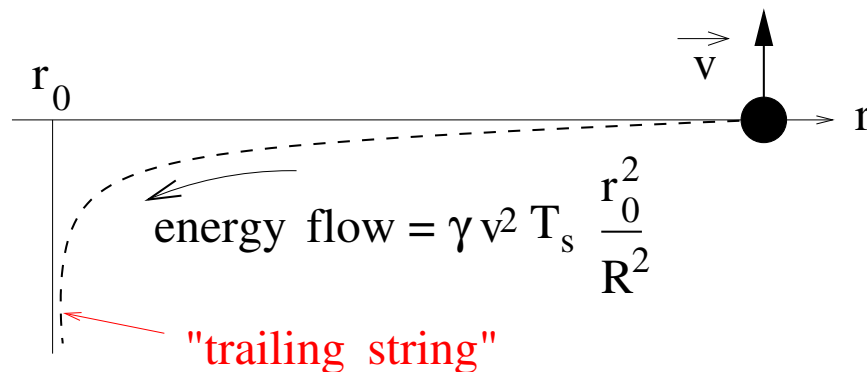
→ study *classical* dynamics of open string in *AdS-BH* background

Nambu-Goto action

$$S_{\text{NG}} = -T_s \int d\sigma d\tau \sqrt{-\det g_{ab}(X^\mu(\sigma, \tau))}$$

- drag quark with velocity v along x -axis
- look for string profile $x(r, t) = x(r) + vt$ minimizing S_{NG}

$$\Rightarrow x(r) = \frac{1}{2} v \frac{R^2}{r_0} \left[\frac{\pi}{2} - \tan^{-1}\left(\frac{r}{r_0}\right) - \coth^{-1}\left(\frac{r}{r_0}\right) \right]$$



$$T_s = \frac{1}{2\pi\ell_s^2} \quad ; \quad r_0 = \pi R^2 T$$

$$\Rightarrow \frac{dE}{dt} = \frac{\pi}{2} \gamma v^2 \sqrt{\lambda} T^2$$

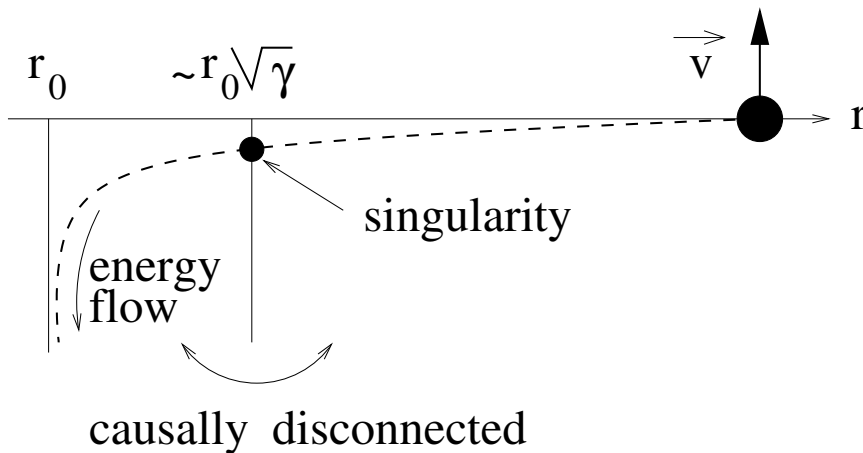
$$(\lambda \gg 1)$$

A physical interpretation

(Marquet, 2008)

(Giecold, Iancu, Mueller, 2009)

What is the physical process responsible for $\frac{dE}{dx}$ in the SYM plasma?



UV/IR correspondence

$r \leftrightarrow Q = \frac{r}{R^2}$ on boundary

energy loss from

$r \lesssim \sqrt{\gamma} r_0 \leftrightarrow Q \lesssim \sqrt{\gamma} T$

→ suggests energy loss arises from radiation of soft components $Q \lesssim \sqrt{\gamma} T$ of heavy quark proper field

purely radiative loss, inducing quark p_T -broadening

Summary



- Two theoretical paths to ΔE_{parton} :
 - perturbative QCD for $\alpha_s \ll 1$
 - AdS/CFT for QCD-like SYM theory and $\lambda \gg 1$
- RHIC data seem to sit in intermediate region $\alpha_s \sim 1$
 - AdS/CFT and possibly AdS/QCD results in region $\lambda \sim 1$ would be very helpful
 - **we should not discard PQCD**
 - only fully predictive approach currently available
 - often valid in region broader than expected
 - applicable to cold matter

