Energy Loss in Strongly Coupled Gauge Theories

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Main Message

Through the **AdS/CFT correspondence**, string theory provides a **useful** tool to study *some* aspects of *certain* **strongly-coupled non-Abelian gauge theories**

Plan

- AdS/CFT $\subset$ Gauge/Gravity Correspondence
- Energy loss from AdS/CFT

My own involvement in this story
(energy loss, screening, radiation damping):
E. Cáceres, AG, hep-th/0605235 (JHEP)
E. Cáceres, AG, hep-th/0606134 (JHEP)
M. Chernicoff, J.A. García, AG, hep-th/0607089 (JHEP)
M. Chernicoff, AG, hep-th/0611155 (JHEP)
M. Chernicoff, AG, 0803.3070 (JHEP)
M. Chernicoff, J.A. García, AG, 0903.2047 (PRL)
M. Chernicoff, J.A. García, AG, 0906.1592 (JHEP)

Motivation: QGP at RHIC

Strongly-Coupled Quark-Gluon Plasma (sQGP)

$$g^2_{QCD} \sim 3-10 \quad \alpha_{QCD} \equiv g^2_{QCD}/4\pi \sim 0.3-1$$

- **Perturbative** expansion unreliable
- (Euclidean) **Lattice** calculations very useful to determine static properties, but NOT dynamical ones
- Can construct effective **phenomenological models**…
- Or can try to do first-principles calculations in a **different (but hopefully similar) theory**

A (Distant) Cousin of QCD…

- $SU(N_c)$ Yang-Mills (w/o quarks): $A^{\mu}_{CC'}(x) \quad C, C' = 1, \ldots, N_c$
  + 6 real massless scalars: $\Phi^{I}_{CC'}(x) \quad I = 1, \ldots, 6$
  + 4 massless Weyl fermions: $\lambda^{A}_{CC'}(x) \quad A = 1, \ldots, 4$
  + carefully synchronized 3-pt and 4-pt interactions

= $SU(N_c)$ Super-Yang-Mills with $\mathcal{N} = 4$ supersymmetry

Is this theory at least qualitatively similar to QCD??

QCD vs. $\mathcal{N}=4$ SYM

- $T=0$:

QCD		$\mathcal{N}=4$ SYM
Asympt. free $dg_{YM}^2/dQ<0$		Conformal $dg_{YM}^2/dQ=0$
Confined in IR		Deconfined
Only massive particles	$\neq$	No mass scale
Linear Potential		Coulomb Potential
Non-Supersymmetric		Supersymmetric

- $T>T_c$:

QCD		$\mathcal{N}=4$ SYM
Approx. conformal $\varepsilon \sim T^4$		Temp. is only scale $\varepsilon \propto T^4$
Deconfined		Deconfined
QGP: Non-abelian plasma of gluons and matter in **fundamental**	$\approx$	XGP: Non-abelian plasma of gluons and matter in **adjoint** rep.
Screened Potential		Screened Potential
No Supersymmetry		Supersymmetry broken

AdS/CFT Correspondence

$\mathcal{N} = 4$ $SU(N_c)$ SYM in 3+1 dim $=$ [Maldacena] **Type IIB String Theory on an asymptotically** $\mathbf{AdS_5 \times S^5}$ **spacetime**

NOTE: in practice, the string description is under calculational control only if spacetime is **weakly curved** and strings are **weakly coupled**

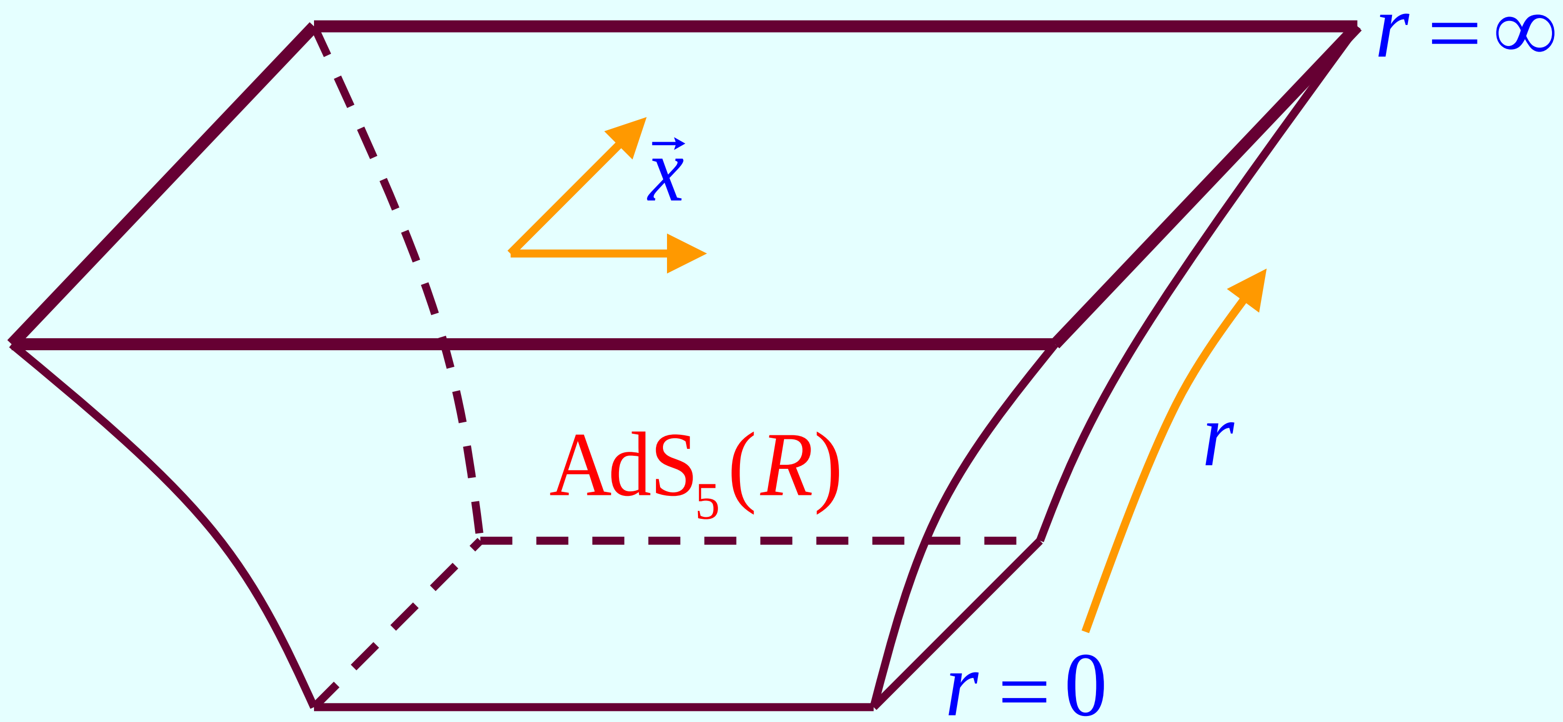
$$\Rightarrow \quad \lambda \equiv g_{YM}^2 N_c \gg 1 \qquad N_c \gg 1$$

(Remember we're ultimately interested in **QCD** at $N_c = 3 \qquad g_{YM}^2 N_c \sim 10-30$)

AdS/CFT Correspondence

IIB ST on asymptotically $\mathrm{AdS}_5 \times \mathrm{S}^5$ **(anti-de Sitter)**

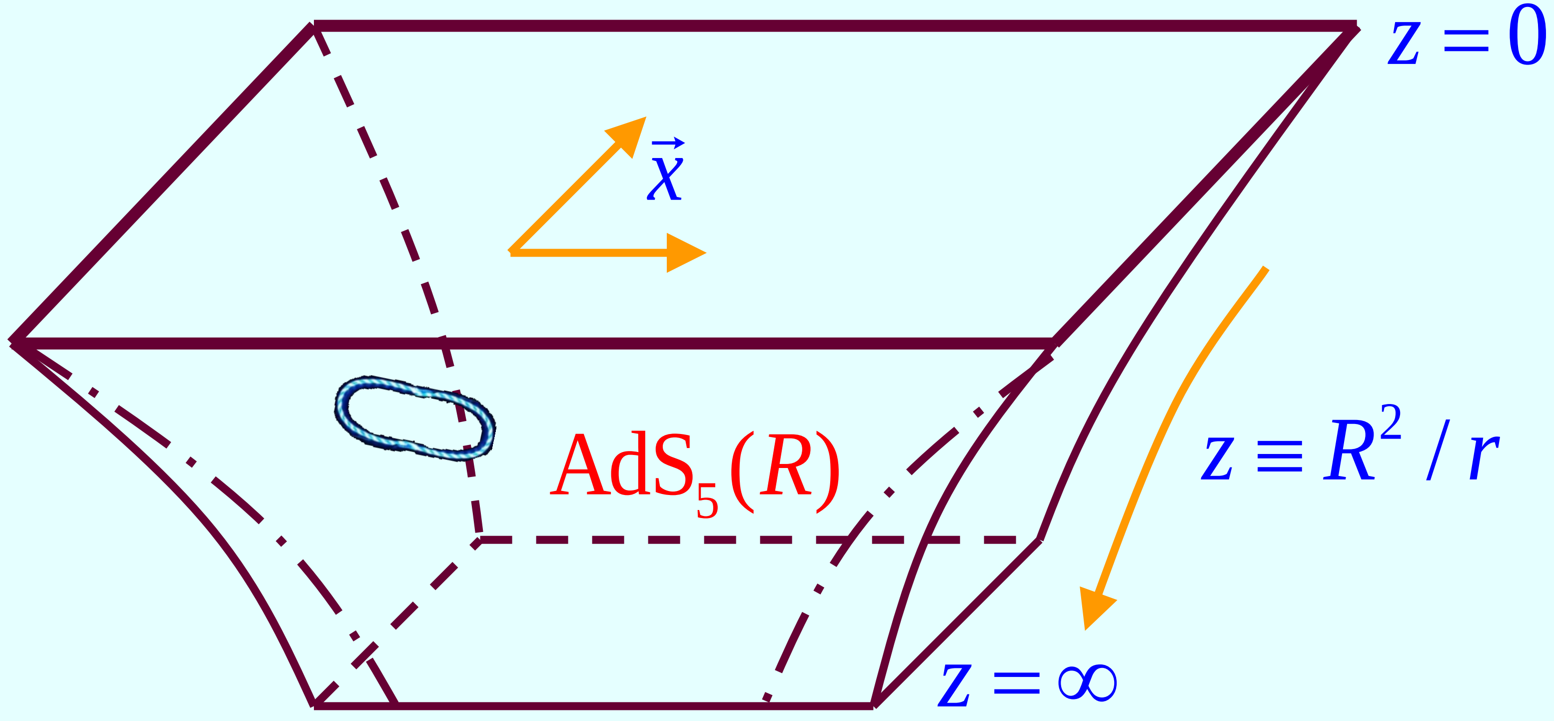
$$ds^2 = (r/R)^2(-dt^2 + d\vec{x}^2) + (R/r)^2 dr^2$$



AdS/CFT Correspondence

IIB ST on asymptotically $\mathrm{AdS}_5 \times \mathrm{S}^5$ **(anti-de Sitter)**

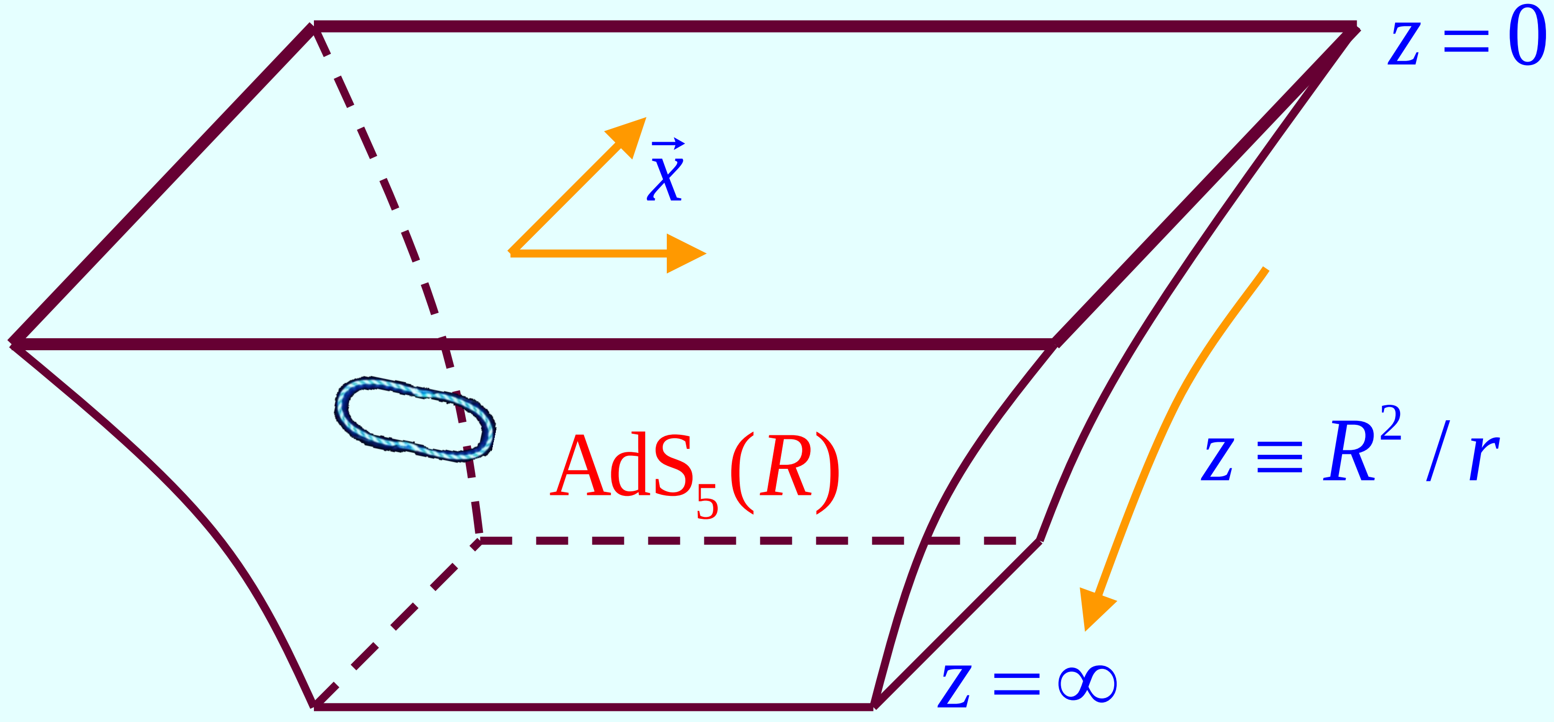
$$ds^2 = (R/z)^2(-dt^2 + d\vec{x}^2 + dz^2)$$



AdS/CFT Dictionary

$\mathcal{N}=4\ SU(N_c)$ SYM $=$ IIB Strings on $\mathbf{aAdS_5 \times S^5}$

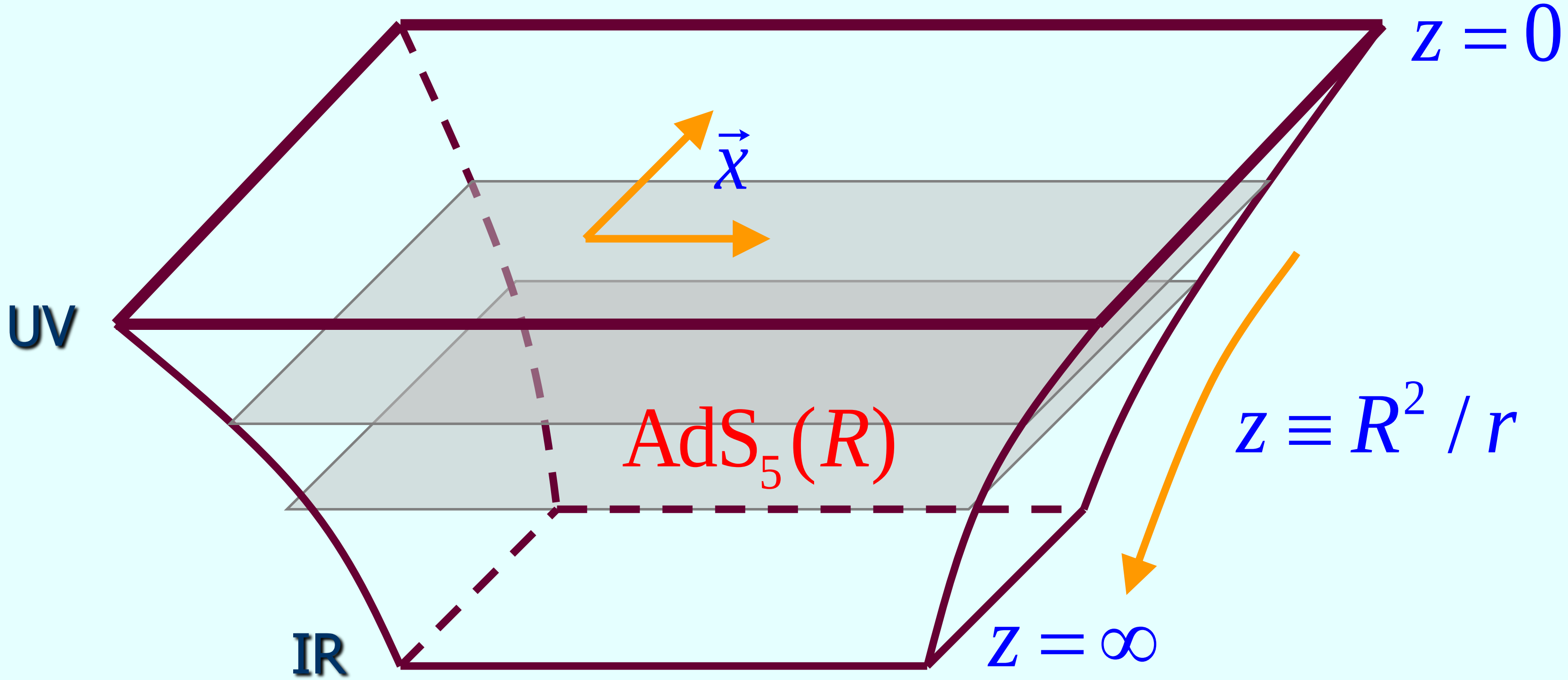
$D=3+1:\quad (t,\vec{x})$ $\qquad D=9+1:\quad (t,\vec{x},z;\theta_1,\ldots,\theta_5)$



AdS/CFT Dictionary

$\mathcal{N} = 4 \; SU(N_c)$ SYM $=$ IIB Strings on $\mathbf{aAdS_5 \times S^5}$

Energy scale $E = 1/z$ [Susskind, Witten]



AdS/CFT Dictionary

$\mathcal{N} = 4$ $SU(N_c)$ SYM $=$ IIB Strings on $\mathbf{aAdS_5 \times S^5}$

Geometry on the RHS is **dynamical**:

Pure $\mathbf{AdS_5}$ spacetime	$\longleftrightarrow$	SYM vacuum
Excitations on $\mathbf{AdS_5}$	$\longleftrightarrow$	Other SYM states
Black hole in $\mathbf{AdS_5}$	$\longleftrightarrow$	Thermal ensemble (deconfined)

AdS/CFT Dictionary

$\mathcal{N}=4$ $SU(N_c)$ SYM = IIB Strings on $\mathbf{aAdS_5 \times S^5}$

Best understood example of a more general **gauge/gravity (string) correspondence**

Other examples relate string theory on different curved spacetimes to certain `QCD-like' gauge theories (w/ less SUSY, confinement, chiral symmetry breaking,…)

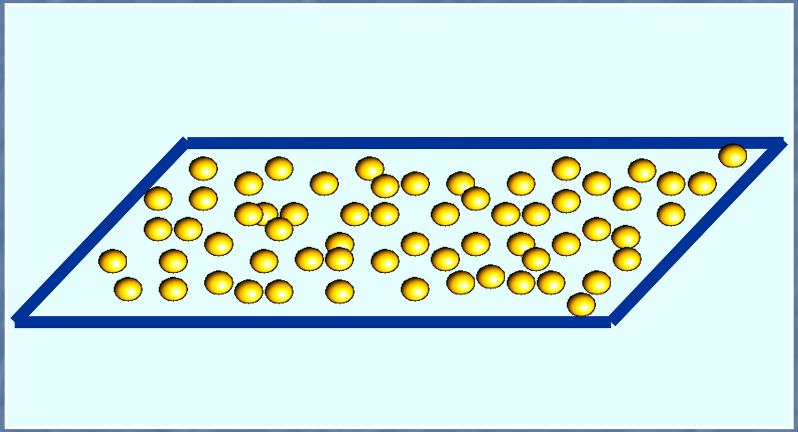
[Sakai-Sugimoto(-Witten); Klebanov-Strassler; Maldacena-Núñez; Polchinski-Strassler; Freedman-Gubser-Pilch-Warner; etc.]

These "top-down" extensions have been obtained by studying other brane systems (varying dim, type of ST, type of background) or deforming known examples

Alternative "bottom-up" approach is to just guess ("AdS/QCD") [Polchinski-Strassler; Erlich,Katz,Son,Stephanov; Da Rold,Pomarol; Gursoy,Kiritsis,Nitti;etc.]

Basic Setup

$\mathcal{N}=4$ $SU(N_c)$ SYM $=$ IIB Strings on $\mathbf{Schw\text{-}AdS_5 \times S^5}$
at finite temp. $T = T_H = 1/\pi z_h$



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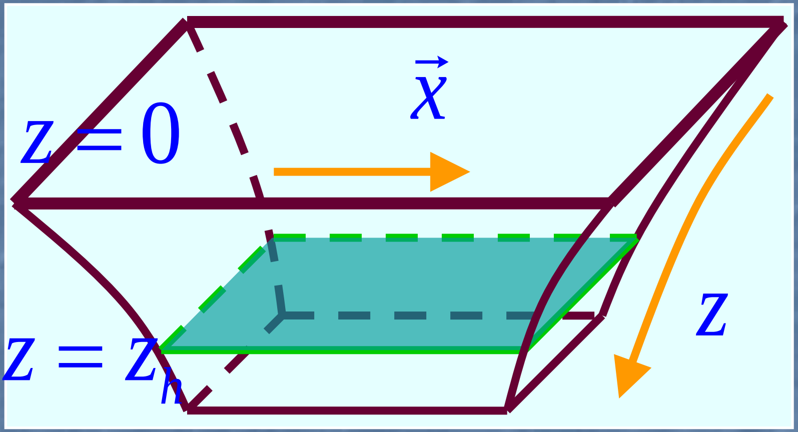
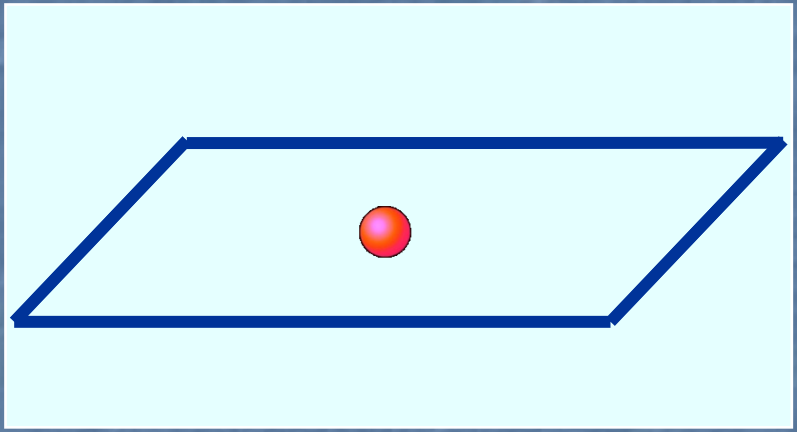


Gluon (+ adjoint scalar & fermion) plasma $=$ Black hole in AdS !!

$$ds^2 = \left(\frac{R}{z}\right)^2 \left(-\left(1-\frac{z^4}{z_h^4}\right) dt^2 + d\vec{x}^2 + \frac{dz^2}{\left(1-\frac{z^4}{z_h^4}\right)} \right)$$

Adding Quarks to SYM



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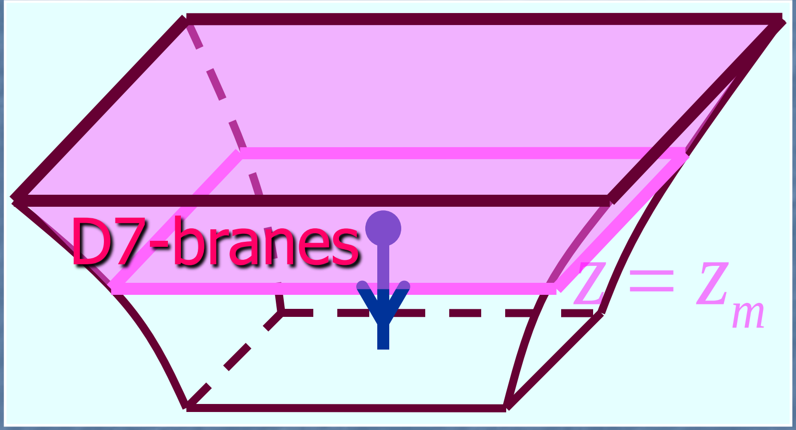


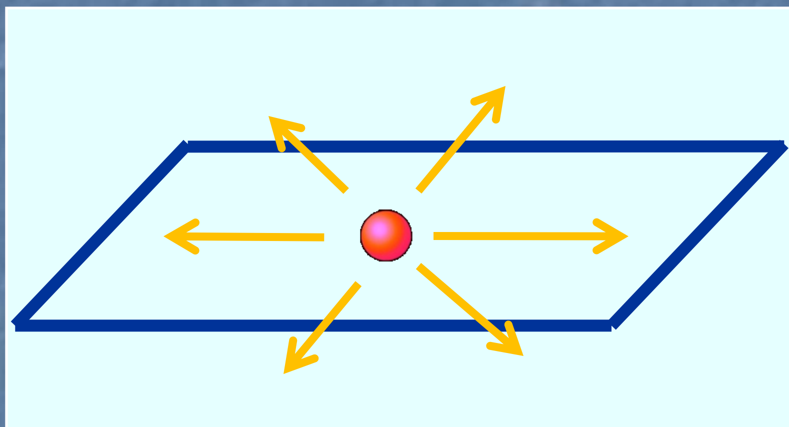
Quark with $m = \sqrt{\lambda} / 2\pi z_m$ = String w/endpoint at $z_m > 0$

[Karch, Katz]

Notice we are coupling 2nd-quantized gluonic (+etc.) fields to **1st-quantized quark**

$$\int Dx(\tau) DA_\mu(x') \exp\left(iS[A(x'), x(\tau)] \right)$$

Adding Quarks to SYM



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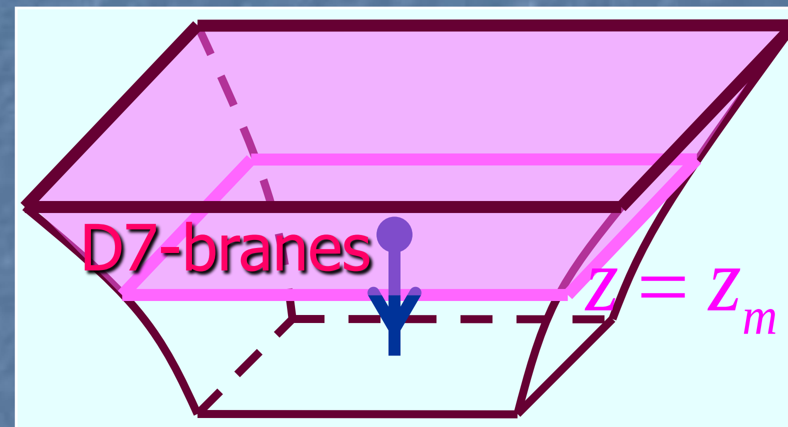

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[Karch, Katz]

Notice we are coupling 2nd-quantized gluonic (+etc.) fields to **1st-quantized quark**

Endpoint $\leftrightarrow$ Quark , String $\leftrightarrow$ Gluonic (+etc.) field

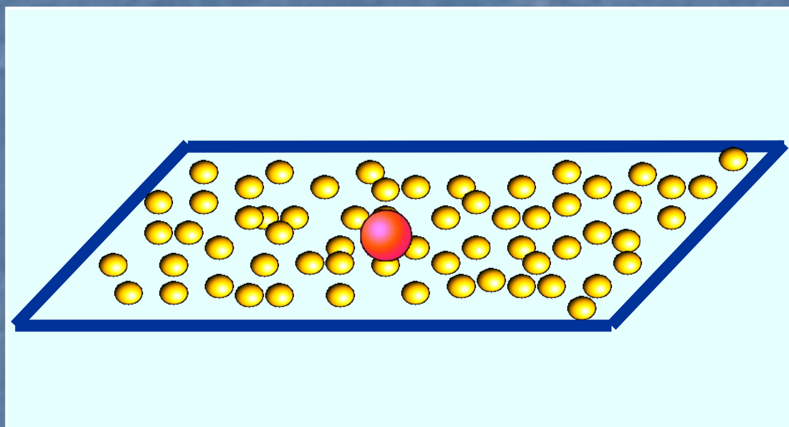
(I.e., 'QCD string' really lives in 5 (+5) dimensions)

Energy Loss from AdS/CFT

This question has been studied in a strongly-coupled $\mathcal{N}=4$ SYM plasma for a variety of probes:

- **Quarks** [Herzog,Karch,Kovtun,Kozcaz,Yaffe; Gubser ; Casalderrey-Solana,Teaney]
- **Mesons** [Peeters,Sonnenschein,Zamaklar; Liu,Rajagopal,Wiedemann; Chernicoff,García,AG; Dusling,Erdmenger,Kaminski,Rust,Teaney,Young]
- **Baryons** [Chernicoff,AG; Athanasiou,Liu,Rajagopal]
- **Gluons** [Chernicoff,AG; Gubser,Gulotta,Pufu,Rocha]
- **k-quarks** [Chernicoff,AG]

Energy Loss from AdS/CFT



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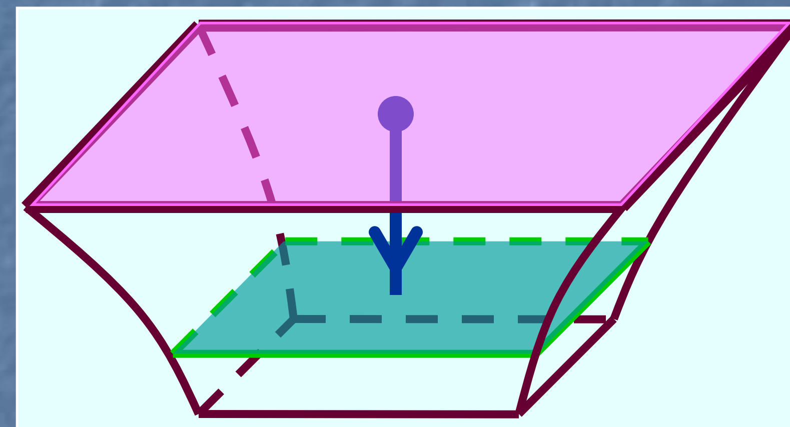
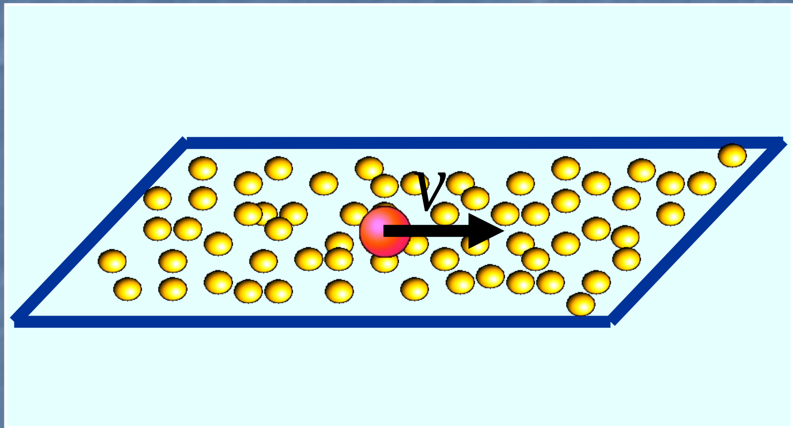


Heavy quark ($m \gg T$) = String from $z = z_m$ to $z = z_h$

Energy Loss: Heavy Quark



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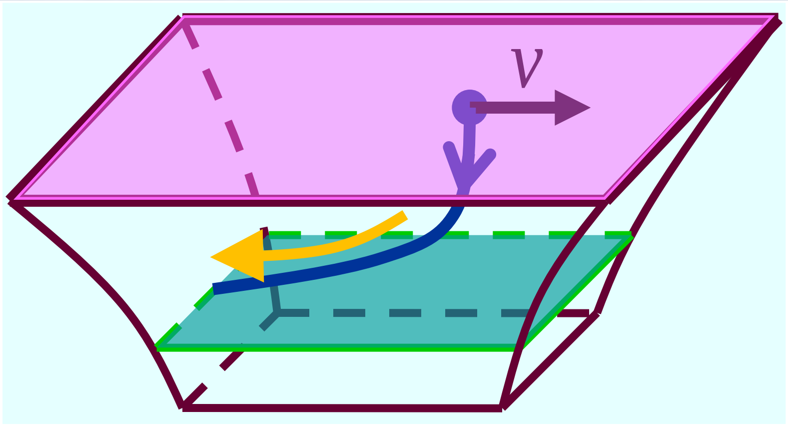
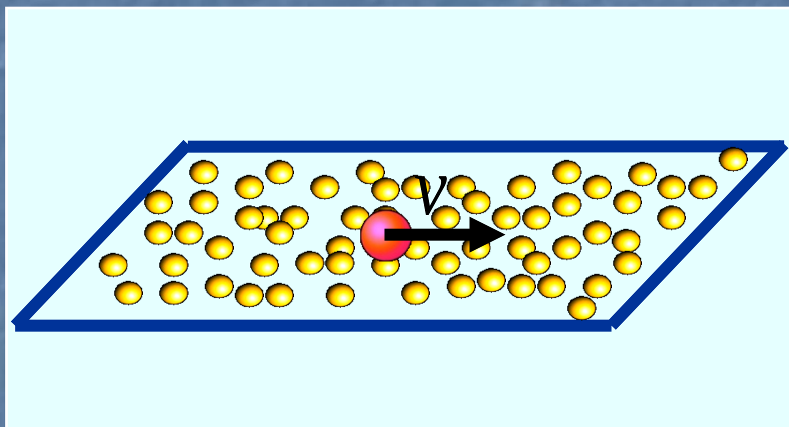


Heavy quark at constant v = String at constant v

Energy Loss Rate: $$\frac{dE}{dx} = -\frac{\pi}{\sqrt{2}}\sqrt{\lambda}T^2\frac{v}{\sqrt{1-v^2}} = \frac{dp_x}{dt}$$

[Herzog,Karch,Kovtun,Kozcaz,Yaffe; Gubser]
(Related work: [Casalderrey-Solana,Teaney])

Energy Loss: Heavy Quark



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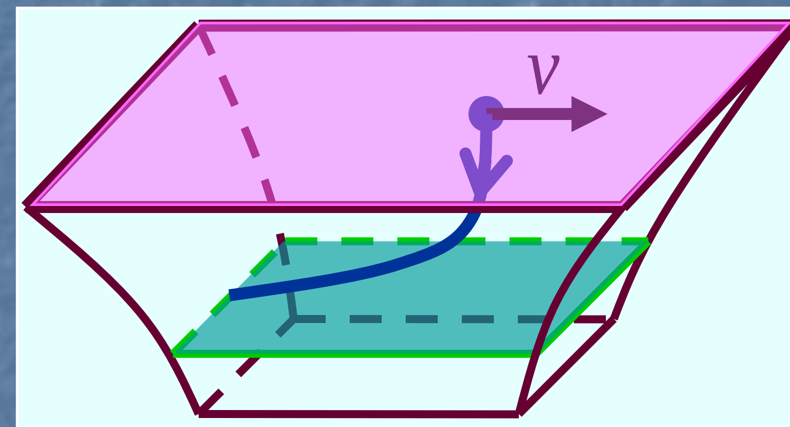


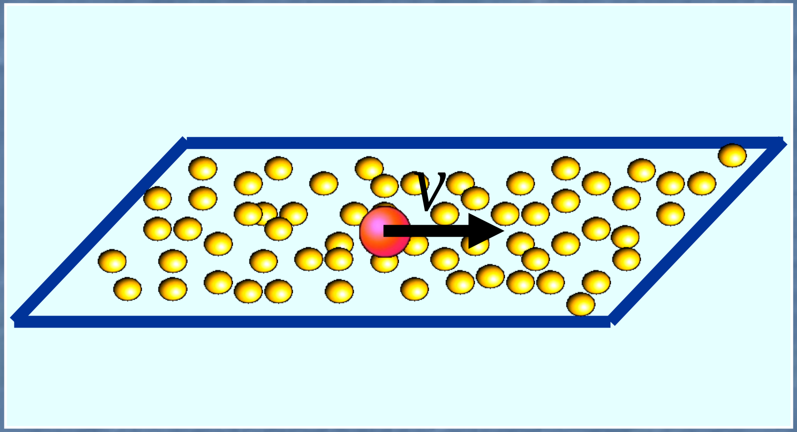
Heavy quark at constant v = String at constant v

$$\Rightarrow \quad p_x(t) = p_x(0)\exp\left(-t/t_r\right) \qquad t_r = \frac{\sqrt{2}m}{\pi\sqrt{\lambda}T^2}$$

E.g., $t_r(\mathrm{charm}) \approx 0.6 - 2.1\ \mathrm{fm/c}$ [Gubser]

cf. pQCD $t_r(\mathrm{charm}) \approx 4 - 12\ \mathrm{fm/c}$ [van Hees,Rapp]

Quark in Plasma



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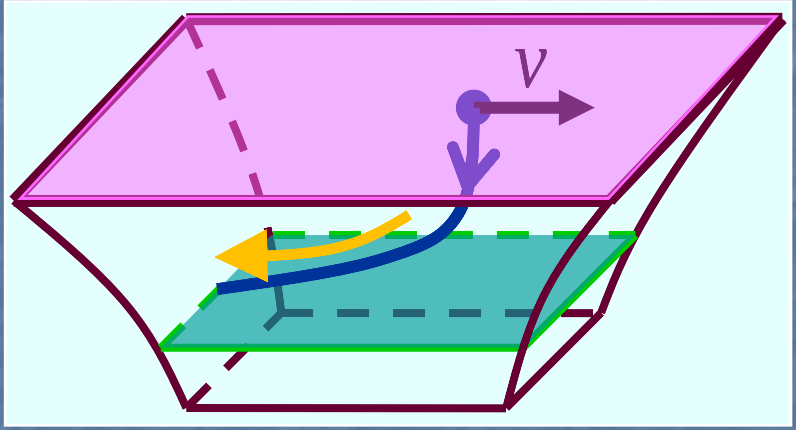


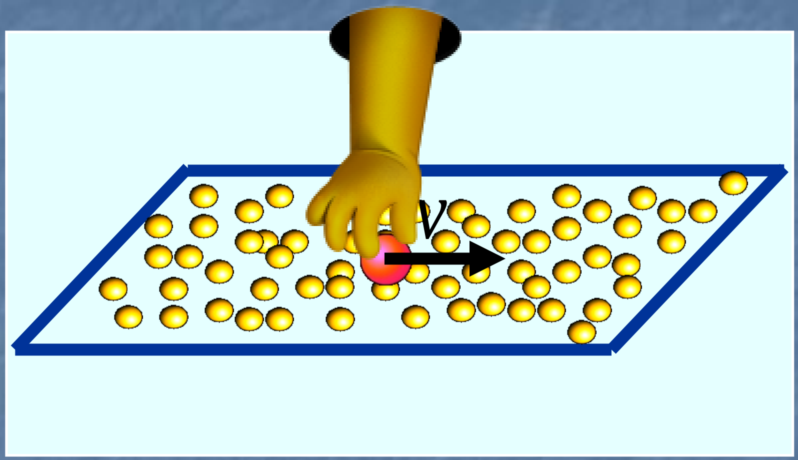
Energy Loss Rate: $$\frac{dE}{dx} = -\frac{\pi}{2}\sqrt{\lambda}T^2 \frac{v}{1-v^2} = \frac{dp_x}{dt}$$

[Herzog,Karch,Kovtun,Kozcaz,Yaffe; Gubser; Casalderrey-Solana,Teaney]

Valid for:

✓ Late-time configuration (near-rest, no external force)

Quark in Plasma



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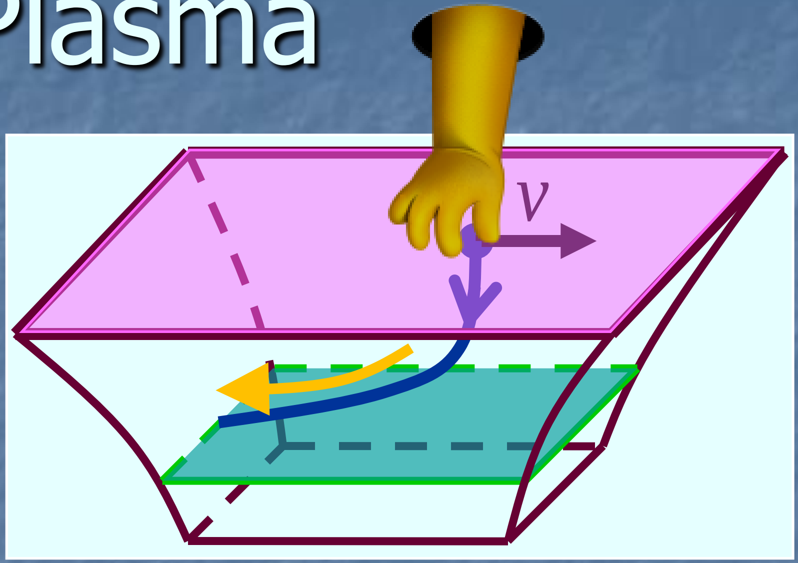

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[Herzog,Karch,Kovtun,Kozcaz,Yaffe; Gubser; Casalderrey-Solana,Teaney]

Valid for:

- ✓ Late-time configuration (near-rest, no external force)
- ✓ Stationary configuration (constant *v*, externally forced)

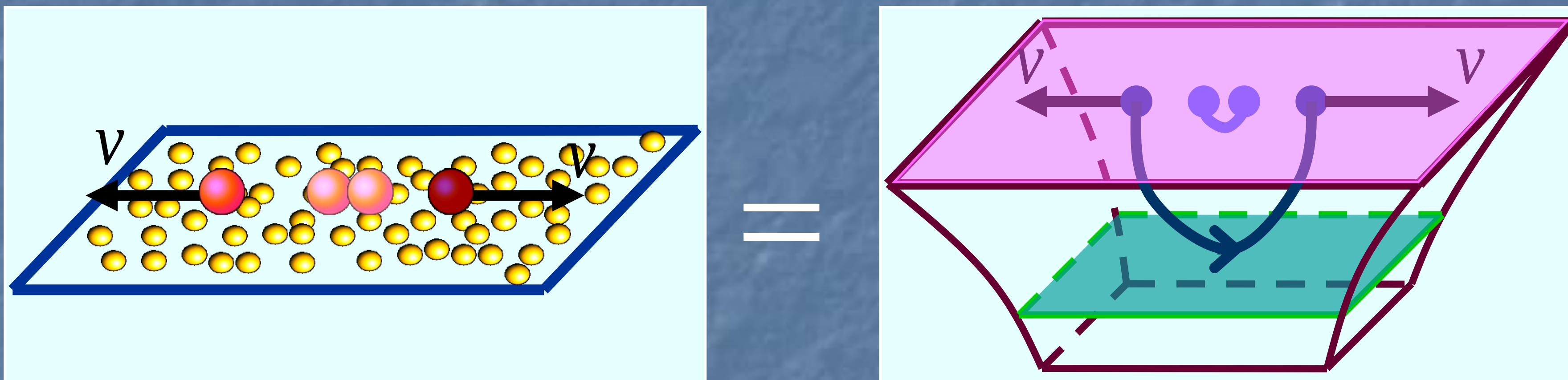
A Tiny Dose of Realism

In the experimental setup:

- Quark is not externally forced, and slows down under the influence of the plasma: configuration is **NOT stationary**
- QGP has finite spatial and temporal extent, so **late-time regime might NOT be accessible** [Peigne,Gossiaux,Gousset]
- Quark is created within plasma together with antiquark
- QGP is expanding and is not isotropic

In our work at finite temperature we addressed the first 3 issues

Energy Loss: Pair Creation



Singlet back-to-back quark-antiquark pair

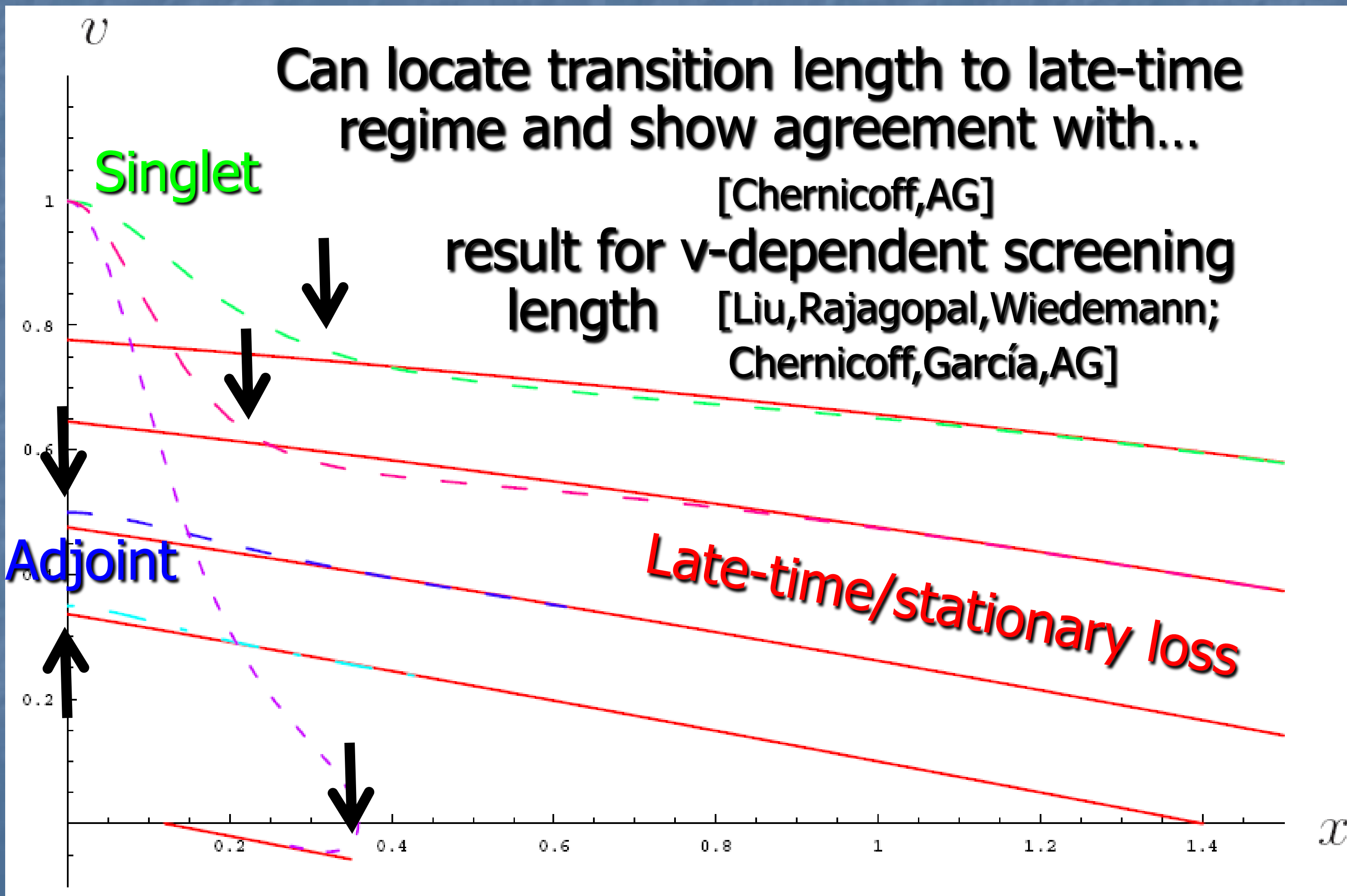
U-shaped string with initially coincident endpoints

[Herzog,Karch,Kovtun,Kozcaz,Yaffe]

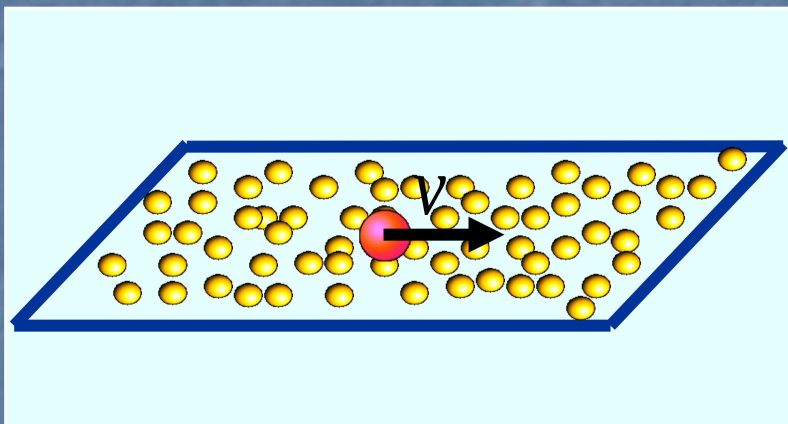
Initial energy loss as in vacuum; ‘start feeling the plasma’ according to stationary formula when q-qbar separation reaches (v-dependent) screening length

[Chernicoff, AG ;
related work: Hatta, Iancu, Mueller]

Back-to-back q-qbar evolution



Energy Loss: Spatial Distribution



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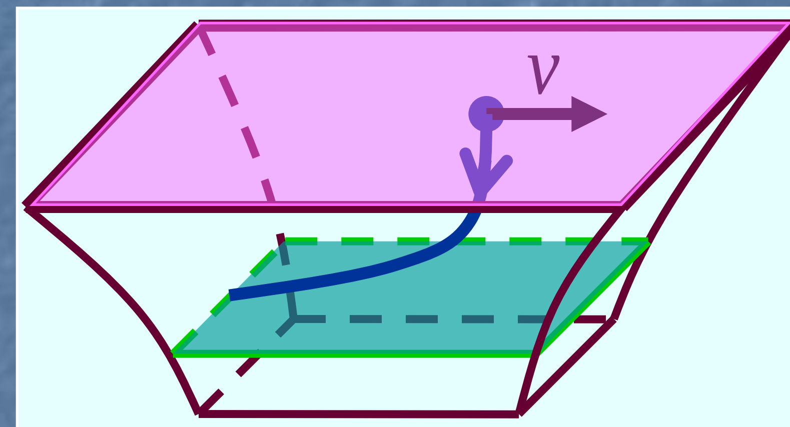


Can determine the spatial profile of dissipated energy from

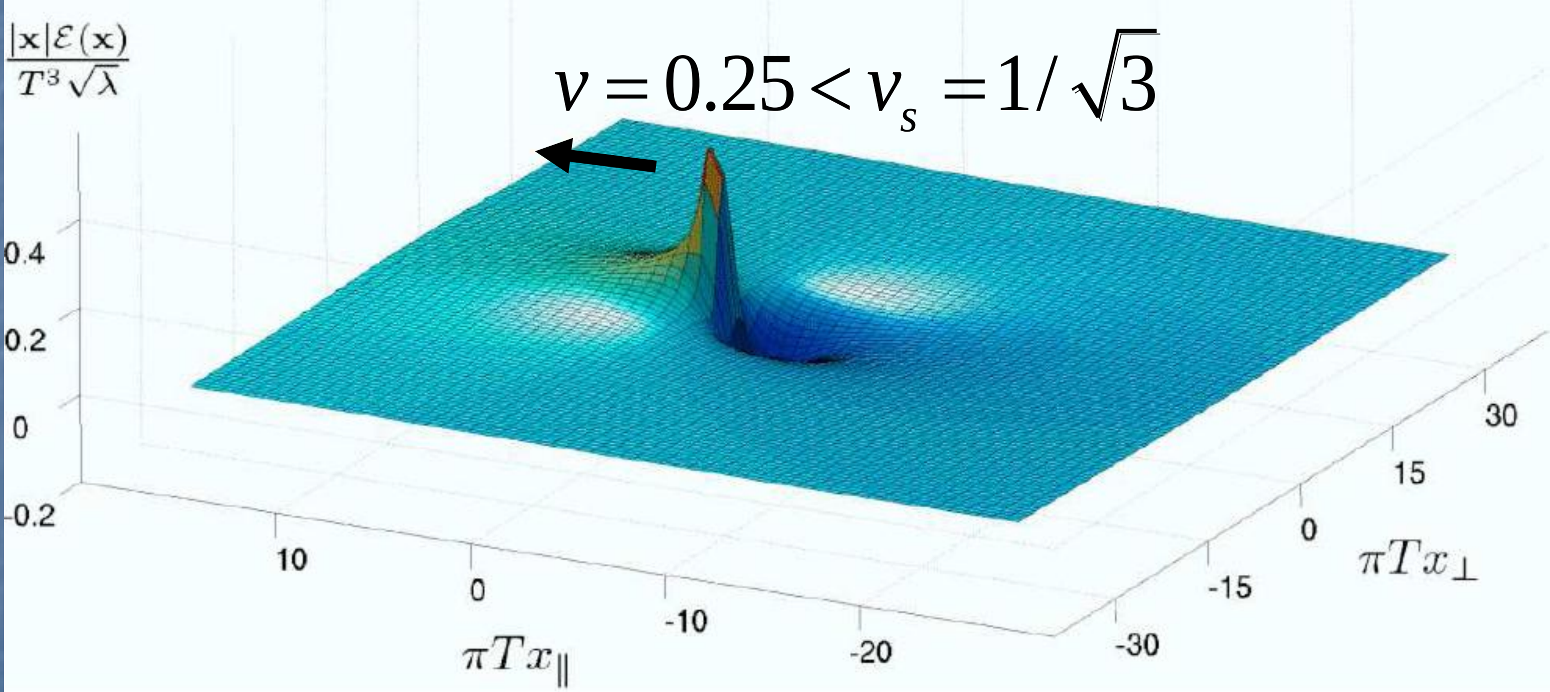
$$\langle T_{\mu\nu}(x) \rangle_{q,v} \quad \leftrightarrow \quad h_{\mu\nu}(x, r = \infty)$$

[Friess,Gubser,Michalogiorgakis; Friess,Gubser,Michalogiorgakis,Pufu; Yarom; Gubser,Pufu; Gubser,Pufu,Yarom; Chesler,Yaffe; Noronha, Torrieri, Gyulassy, etc.]

Energy Loss: Spatial Distribution

Energy density in wake generated by the quark

[Gubser,Pufu,Yarom; Chesler,Yaffe]



From: Chesler,Yaffe, arXiv:0706.0368

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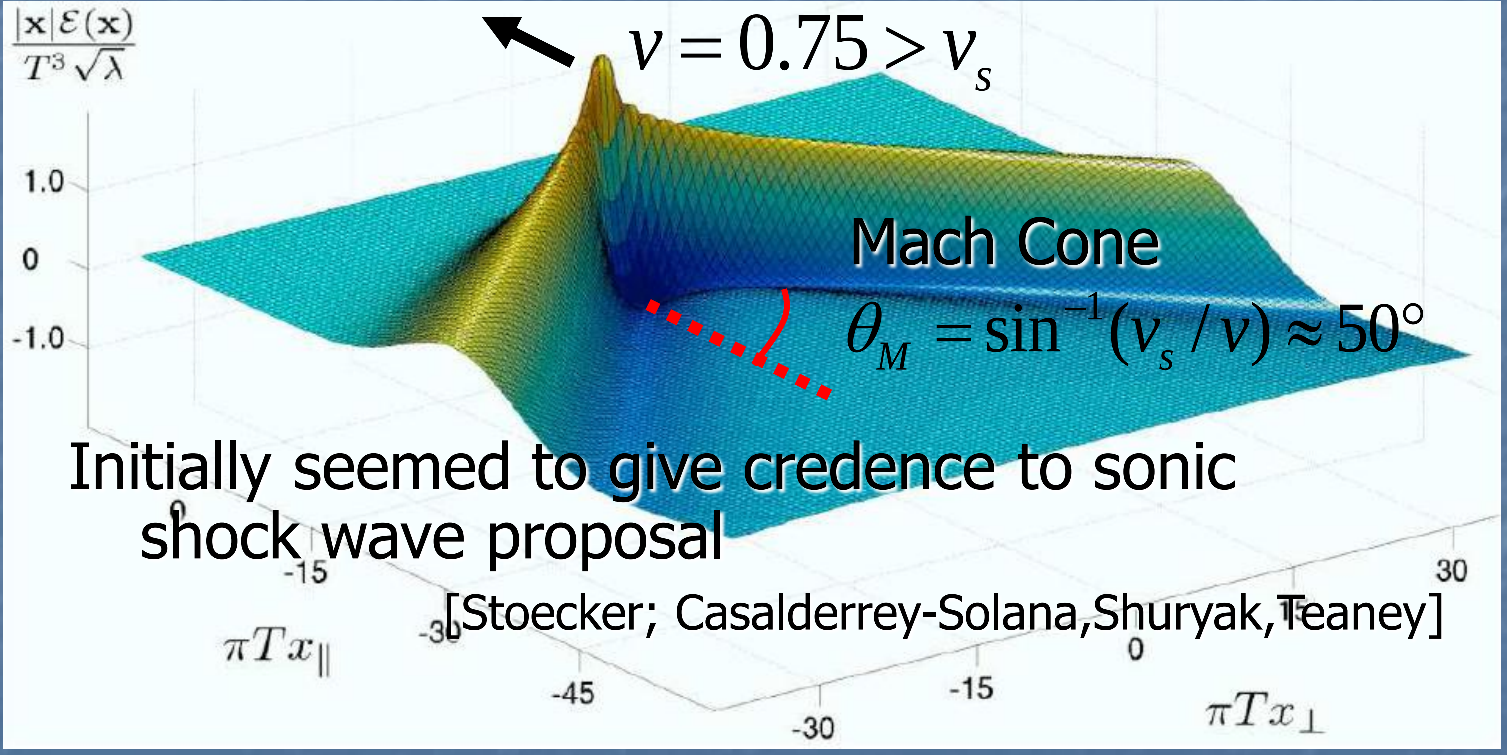

$v = 0.75 > v_s$

Mach Cone

$\theta_M = \sin^{-1}(v_s / v) \approx 50°$

Initially seemed to give credence to sonic shock wave proposal

[Stoecker; Casalderrey-Solana,Shuryak,Teaney]

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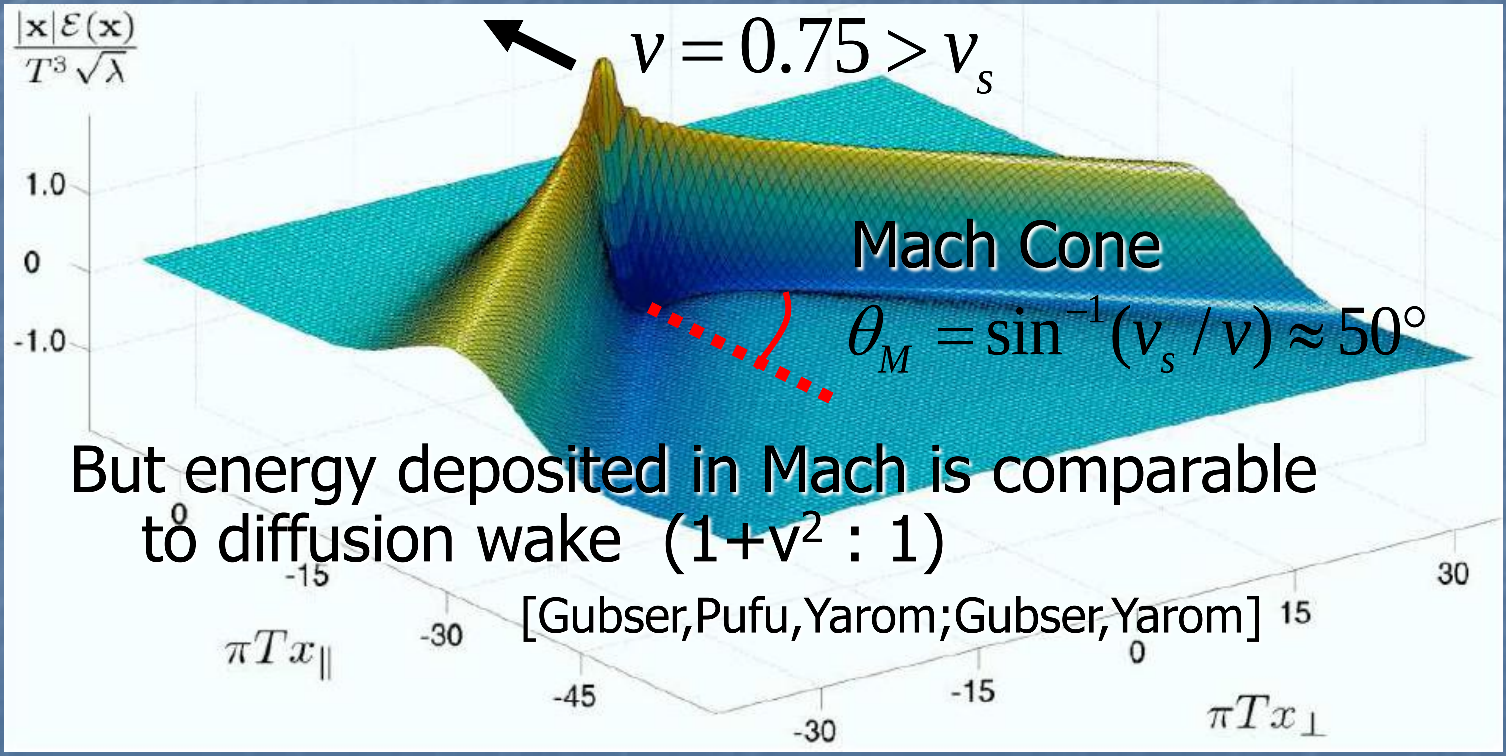

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But energy deposited in Mach is comparable to diffusion wake $(1+v^2 : 1)$

[Gubser,Pufu,Yarom;Gubser,Yarom]

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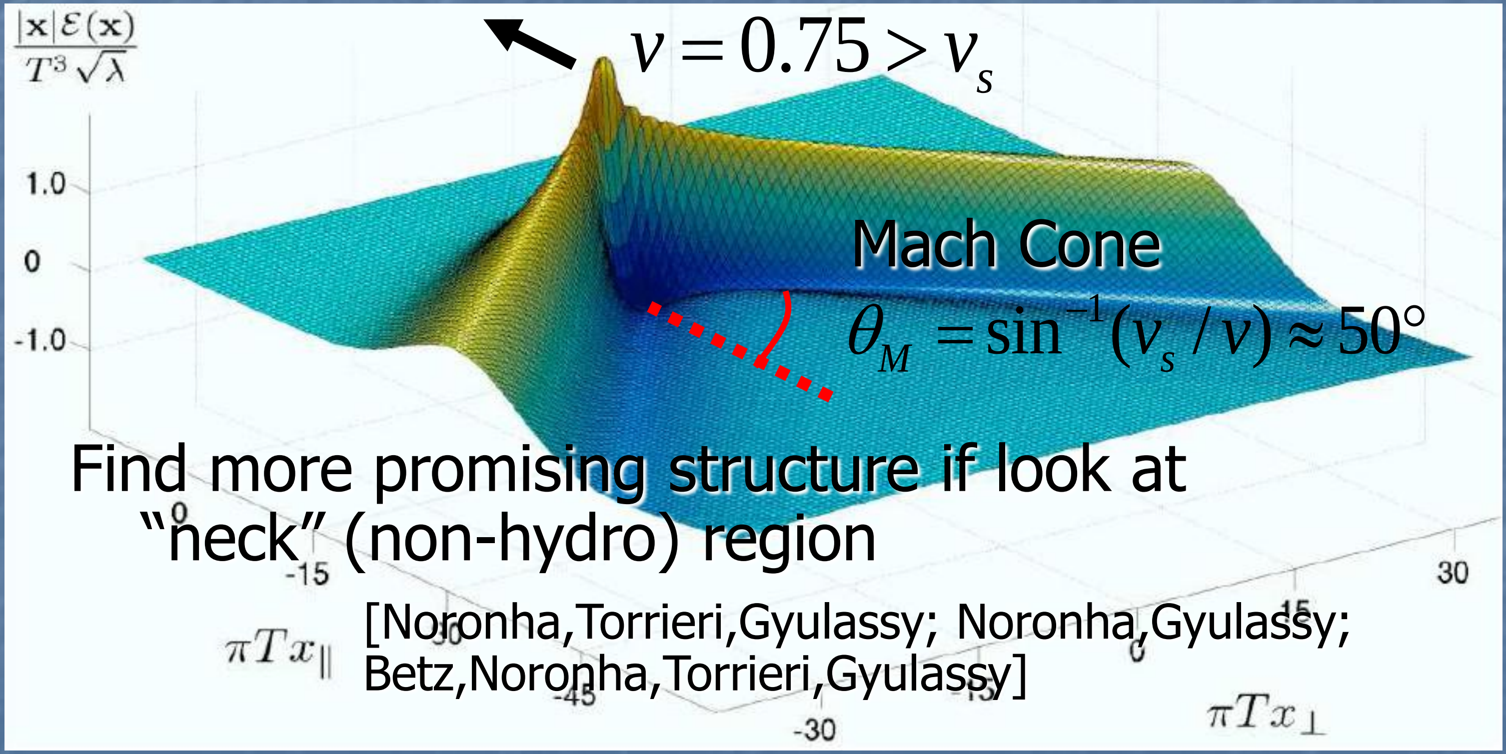
Energy Loss: Spatial Distribution

Energy density in wake generated by the quark

[Gubser,Pufu,Yarom; Chesler,Yaffe]



$v = 0.75 > v_s$

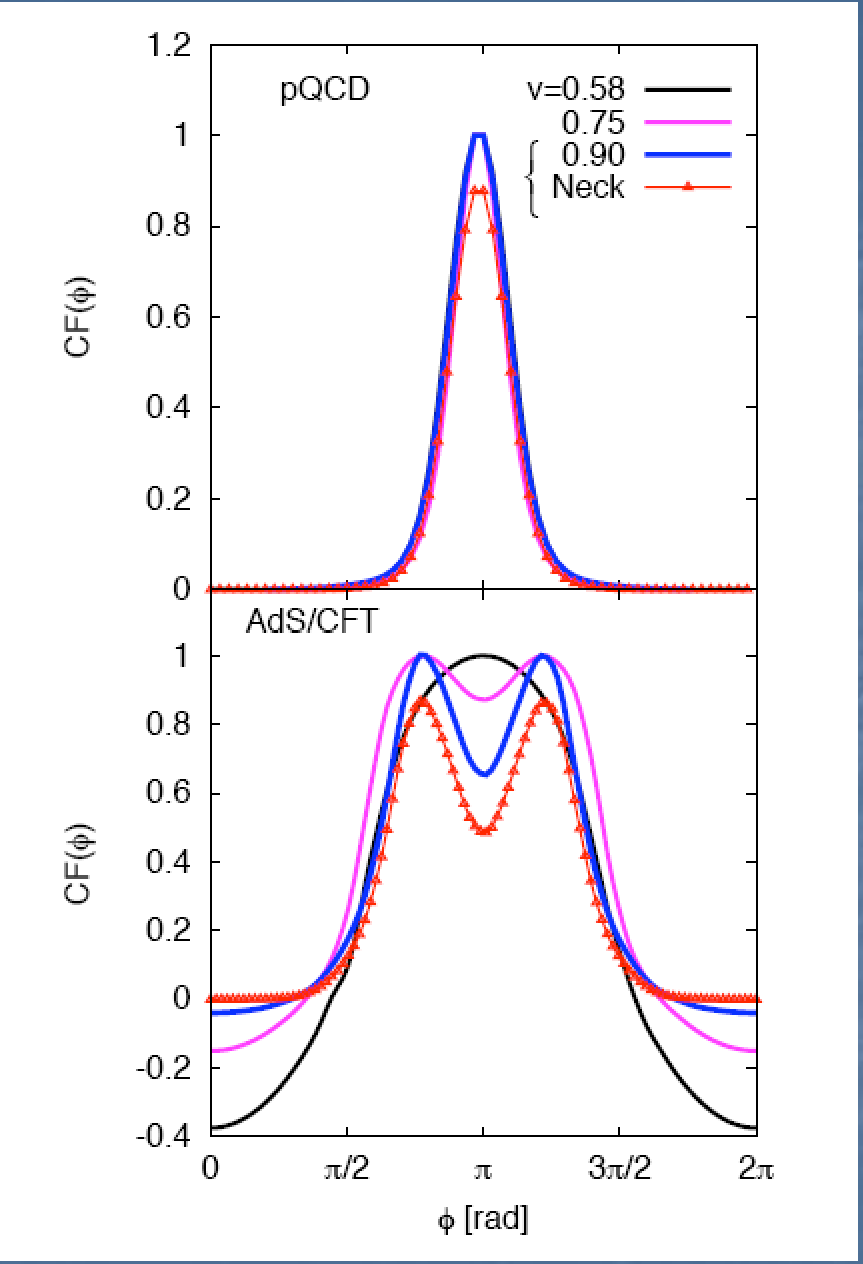
Mach Cone

$\theta_M = \sin^{-1}(v_s / v) \approx 50°$

Find more promising structure if look at "neck" (non-hydro) region

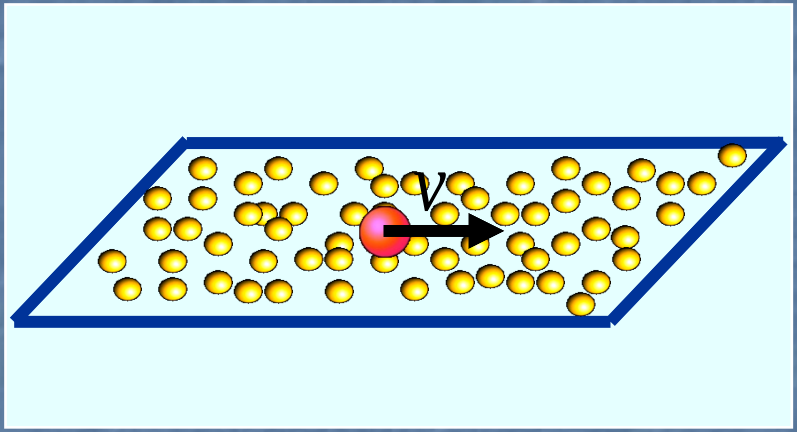
[Noronha,Torrieri,Gyulassy; Noronha,Gyulassy; Betz,Noronha,Torrieri,Gyulassy]

From: Chesler,Yaffe, arXiv:0706.0368



From: Betz,Noronha,Gyulassy,Torrieri, arXiv:0807.4526

Momentum Broadening



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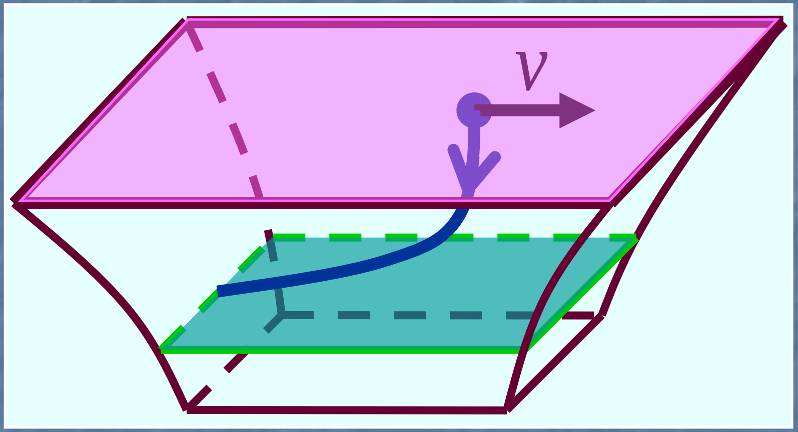


Jet-quenching parameter:

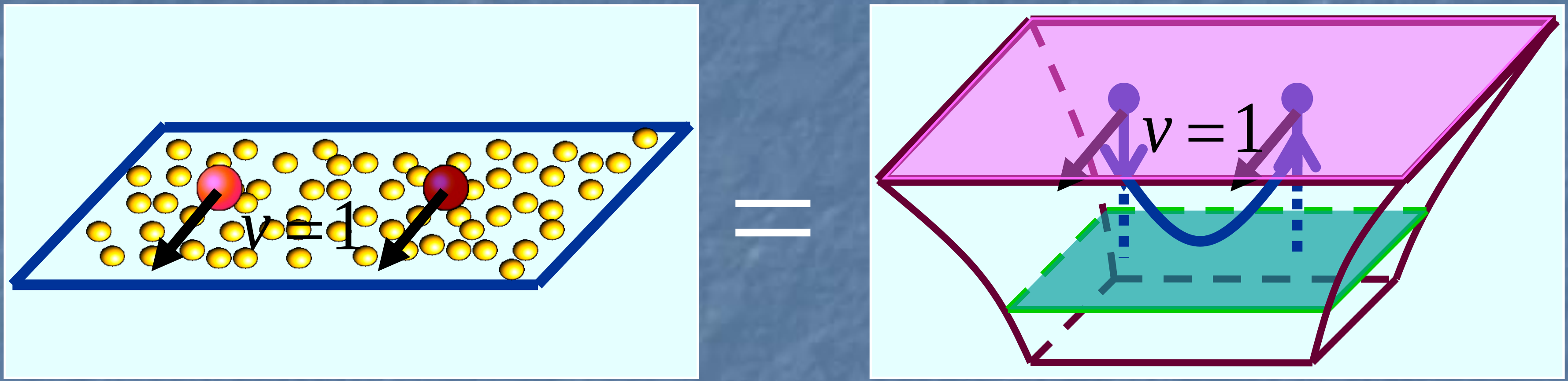
$$\hat{q}_T \equiv \frac{\left\langle p_\perp^2 \right\rangle}{d} = \frac{2\pi\sqrt{\lambda}T^3}{v\left(1-v^2\right)^{1/4}}$$

$$\hat{q}_L \equiv \frac{\left\langle \left(\Delta p_L\right)^2 \right\rangle}{d} = \frac{\pi\sqrt{\lambda}T^3}{v\left(1-v^2\right)^{5/4}}$$

(valid for $v \leq v_{\max}$)

[Gubser; Casalderrey-Solana,Teaney]

Momentum Broadening



Different approach, based on lightlike Wilson loop:

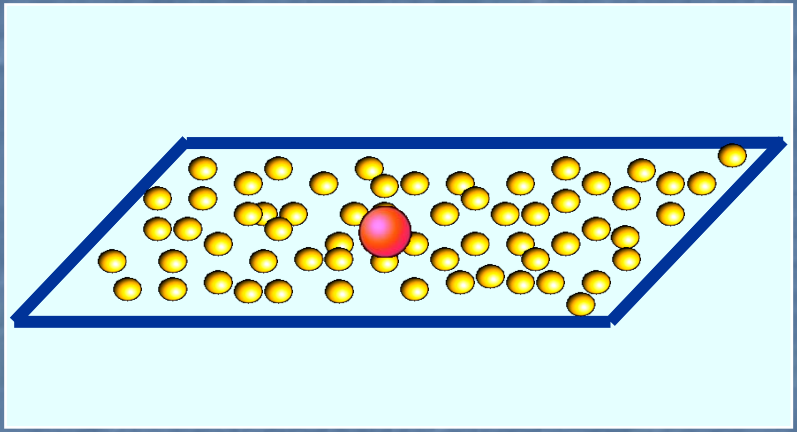
$$\hat{q}_{LRW} \equiv -\frac{4\sqrt{2}}{L_- L^2}\log\langle W_A(C)\rangle = \frac{\pi^{3/2}\Gamma\left(\frac{3}{4}\right)\sqrt{g_{YM}^2 N}T^3}{2\Gamma\left(\frac{5}{4}\right)}$$

[Liu,Rajagopal,Wiedemann]

$\hat{q}_{LRW} = 4.5\,\mathrm{GeV}^2/\mathrm{fm}$ at $T = 300\,\mathrm{MeV}$, $\lambda = 6\pi$

(cf. $\hat{q}_{RHIC} \approx 5-15\,\mathrm{GeV}^2/\mathrm{fm}$ [Dainese, Loizides, Paic; Eskola et al.])

Thermal Fluctuations



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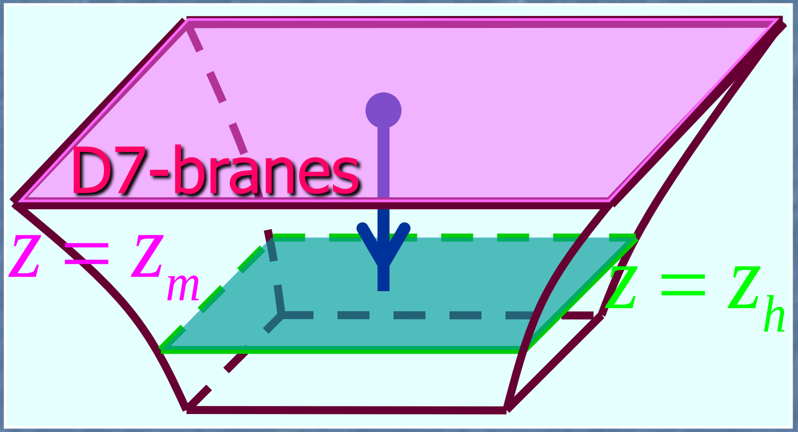
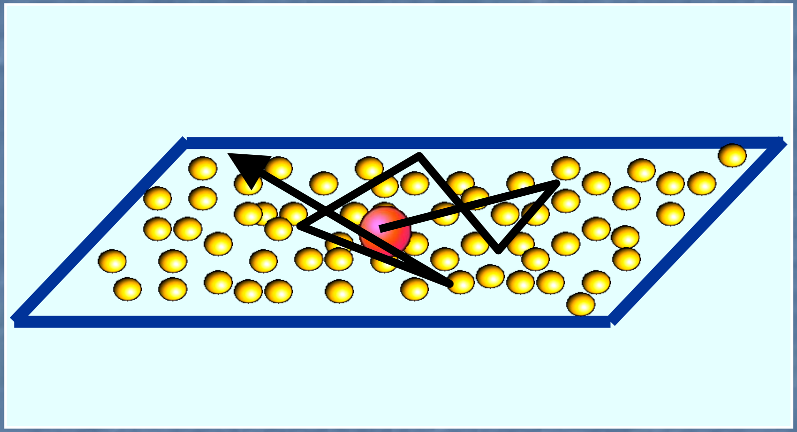


Heavy quark in plasma = String on black hole geometry

Thermal Fluctuations



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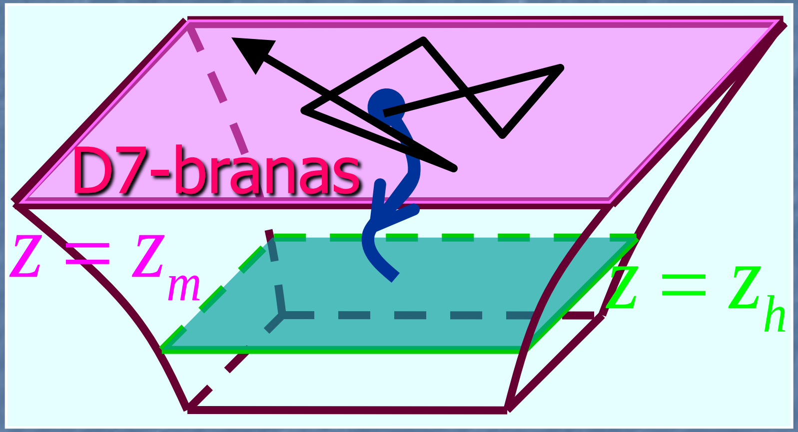

Heavy quark in plasma = String on black hole geometry

Stochastic motion (generalized Langevin equation) arises from Hawking radiation along string! [Son,Teaney; de Boer,Hubeny,Rangamani,Shigemori; Giecold,Iancu,Mueller]

Conclusions

1) AdS/CFT is an efficient tool for calculations in certain strongly-coupled gauge theories, and already makes suggestions for phenomenological models
2) The sQGP produced at RHIC or LHC appears to be a promising site for **eventually** obtaining firm experimental predictions from AdS/CFT (& string theory)…
3) For this, however, **a lot remains to be done**! In particular, we must further refine our description, e.g., incorporating finite size and time-dependence of the plasma, out-of-equilibrium and hadronization stages, etc.

[Nastase; Shuryak,Sin,Zahed; Janik,Peschanski; Nakamura,Sin; Kajantie, Tahkokallio; Bak,Gutperle,Karch; Heller,Janik; Kim,Sin,Zahed; Battacharyya,Hubeny,Minwalla,Rangamani; etc.]

Conclusions

4) Phenomenological, model-dependent predictions are already within reach...

5) ...but firm first-principles predictions we would have to either:

a) Advance from known 'QCD-like' duals to exact **QCD dual** (and somehow handle asymptotically-free region, where spacetime would be highly curved)

or

b) Find sufficiently '**universal**' quantities (e.g., shear viscosity, energy density?, charmonium suppression?, bulk viscosity?, energy loss into sound/diffusion?, photo-production?, etc.)