Holographic Energy Loss.

Herzog, AK, Kovtun, Kozcaz, Yaffe, JHEP 0607 (2006) 013

Chesler, Jensen, AK, Yaffe, Phys.Rev. D79 (2009) 125015

Janiszewski, AK, arxiv:1106.4010

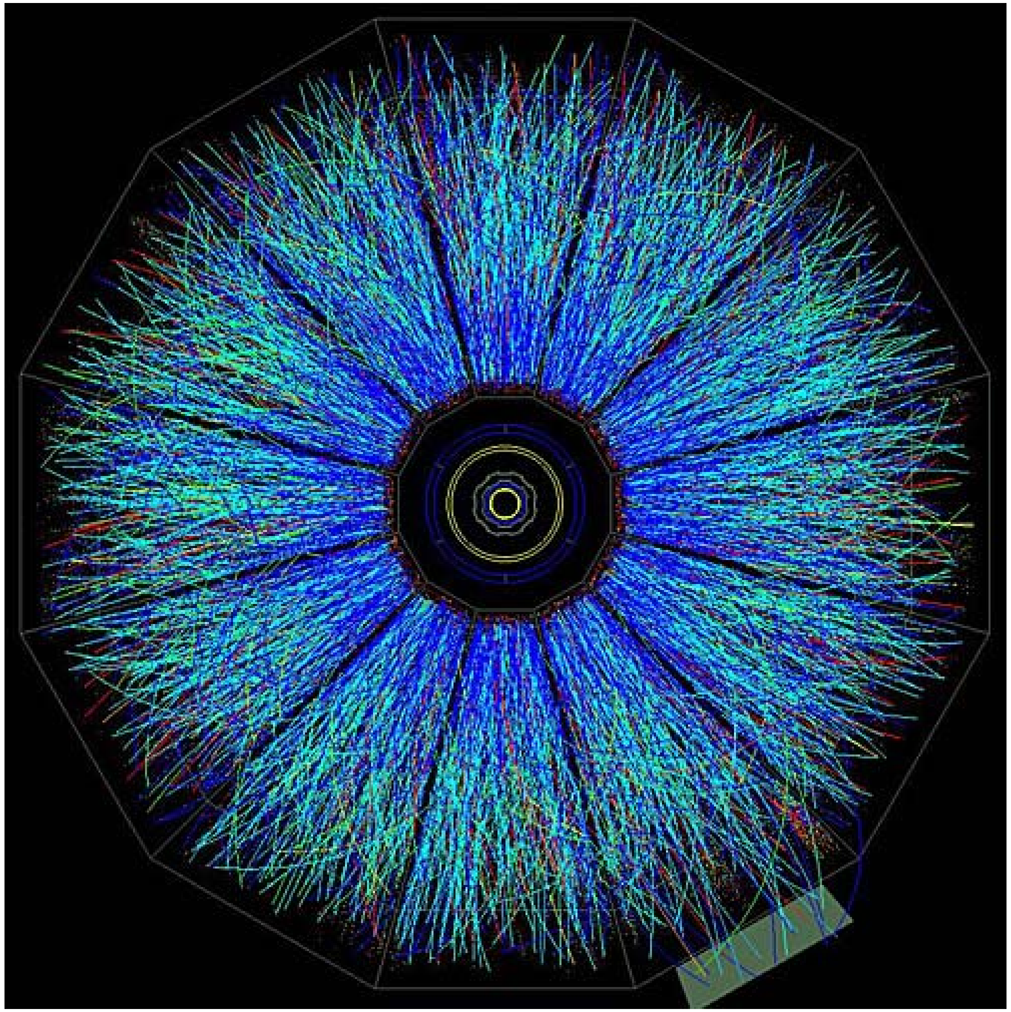
Introduction and Motivation

Can stringy theory help to understand heavy ion collisions (RHIC,LHC) ?

RHIC

…. bird's perspective

RHIC:



…. experimentalists perspective.

RHIC:

…. string theorist’s perspective.

Science at RHIC:

Collides high energy gold nuclei.

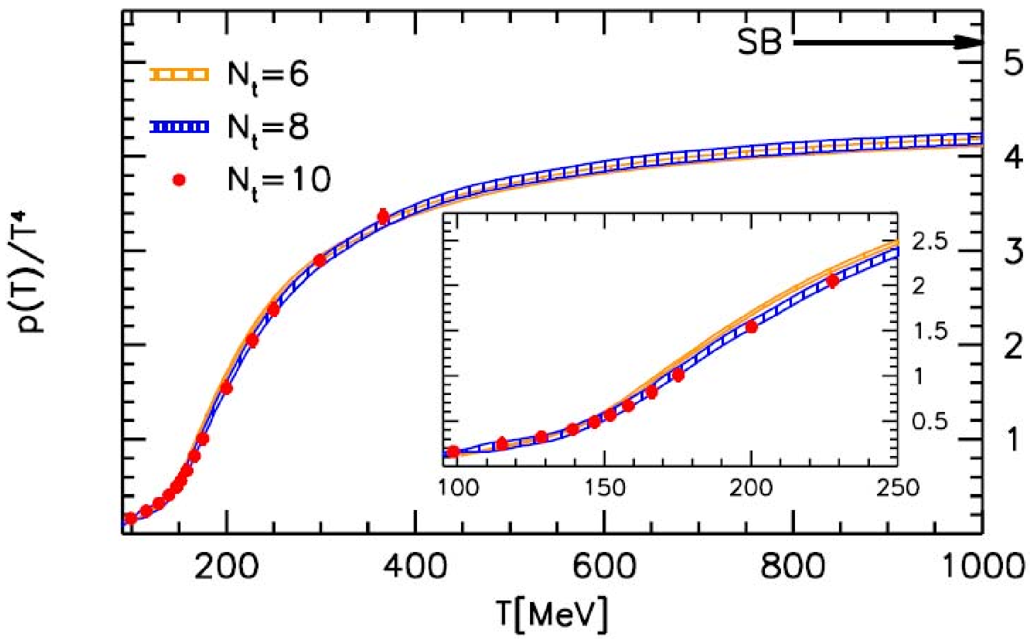
Goal: Study Thermodyamics and
Hydrodynamics of QCD at temperatures
of order Λ_{QCD}

Thermo: Equilibrium Properties
Hydro: effective theory describing small, long wavelength fluctuations around equilibrium

QCD Thermodynamics and Hydrodynamics.

QCD thermodynamics:

QCD thermodynamics is under good theoretical control using lattice gauge theory.

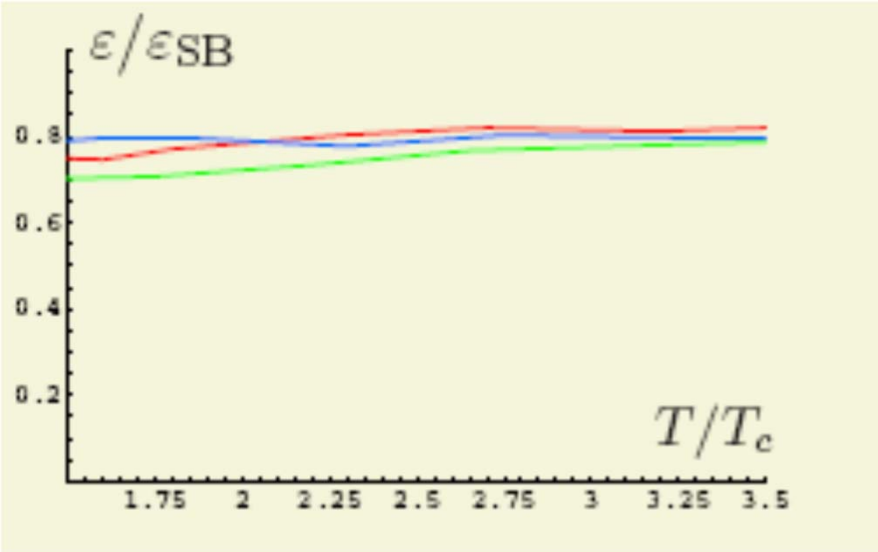


Borsanyi et al, hep-lat/0106019

Pressure (T)

(2+1 flavors)

What do we know about QCD thermo?



ε_{sb}, s_{sb} : entropy/energy density of free gas.

at very large T the coupling goes to zero, so s has to become s_{sb}

$$s \approx 0.75\, s_{SB}$$

at T ~ Λ_{QCD}

free gas with smallish residual interactions?

Near Equilibrium Dynamics:

Fireball at best in *local* equilibrium!

Theoretically only very poorly understood.

Hydro: effective theory describing small, long wavelength fluctuations around equilibrium

Hydro degrees of freedom: conserved charges!

$T_{\mu 0}$ $\quad$ J_0

present in any theory: ε, π_i

Hydro as an effective theory

Hydro equations of motion: $\partial^\mu T_{\mu\nu} = 0$

(conservation laws)

Speed of sound

and constitutive relations:

Energy density

$$T^{ij} = \delta^{ij}\left[P + v_s^2\delta\epsilon + \frac{1}{2}\xi(\delta\epsilon)^2 - v_s^2\frac{\pi^2}{\epsilon+P}\right] + \\ + \frac{\pi^i\pi^j}{\epsilon+P} - \gamma_\eta\left(\partial^i\pi^j + \partial^j\pi^i - \frac{2}{3}\delta^{ij}\,\partial\cdot\pi\right) + \ldots$$

Pressure

Shear viscosity

Momentum density

Kubo Formulas.

(from Arnold, Moore & Yaffe)

Shear viscosity

$$\eta = \frac{1}{20} \lim_{\omega \to 0} \frac{1}{\omega} \int d^4x \, e^{i\omega t} \langle [\pi_{lm}(t,\mathrm{x}), \, \pi_{lm}(0)] \rangle_{\mathrm{eq}} \, ,$$

$$\zeta = \frac{1}{2} \lim_{\omega \to 0} \frac{1}{\omega} \int d^4x \, e^{i\omega t} \langle [\mathscr{P}(t,\mathrm{x}), \, \mathscr{P}(0)] \rangle_{\mathrm{eq}} \, ,$$

$$\sigma = \frac{1}{6} \lim_{\omega \to 0} \frac{1}{\omega} \int d^4x \, e^{i\omega t} \langle [j_i^{\mathrm{EM}}(t,\mathrm{x}), \, j_i^{\mathrm{EM}}(0)] \rangle_{\mathrm{eq}} \, ,$$

$$D_{\alpha\beta} = \frac{1}{6} \lim_{\omega \to 0} \frac{1}{\omega} \int d^4x \, e^{i\omega t} \langle [j_i^{\alpha}(t,\mathrm{x}), \, j_i^{\gamma}(0)] \rangle_{\mathrm{eq}} \, \Xi^{-1}_{\gamma\beta} \, .$$

Stress-Energy 2-pt function.

Need correlation functions in microscopic theory.

Drag on a heavy quark.

Another interesting hydrodynamic quantity in QCD is the drag force excerted on a quark.

Energetic quarks see “interior” of fireball.

$$\frac{dP}{dt} = -\mu P$$

Also can be obtained from a correlation function via a Kubo formula (Solana-Teaney)

QCD Hydro from the lattice?

These are real time correlation functions!

Non-equilibrium physics, real time fluctuations around thermal equilibrium.

Extremely difficult on the lattice, since lattice gauge theory is tied to a Euclidean formulation.

QCD Hydro from perturbation theory?

Of course at very high T (weak coupling) everything is under control…

At weak coupling transport coefficients can be calculated using perturbation theory.

(Actual calculation by Arnold, Moore and Yaffe first matches to Boltzman equation and then to Hydro)

Weak Coupling Results (Arnold, Moore & Yaffe)

$$\eta = \kappa \frac{T^3}{g^4 \log g^{-1}}$$

κ depends on N_f and N_c

Note that the viscosity goes **up** as the coupling goes to zero!!

Weak Coupling Results

The drag on a heavy quark on the other hand goes to zero as we turn of the coupling.

Explicit formulas have been worked out by Moore and Teaney .

Summary: Theory Expectations

At asymptotically large Temperature:

Stefan-Boltzman thermodynamics
large viscosity
no drag

(free) Quark Gluon Plasma

Pre-RHIC believe: around $T=T_c$ qualitatively similar behavior, e.g. $s \sim ¾ s_{SB}$

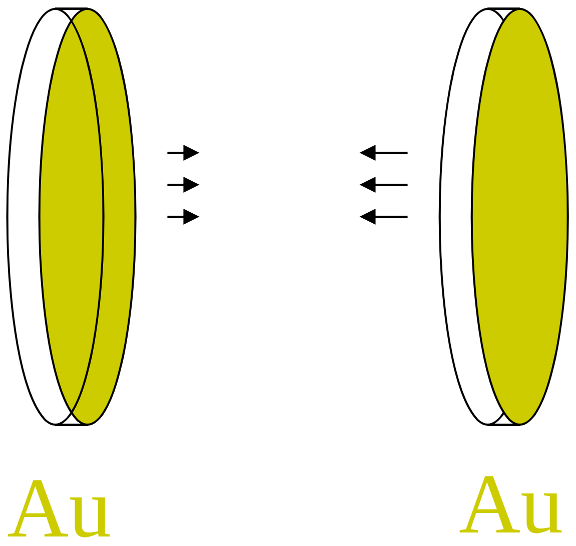
Hydro and Thermo at RHIC

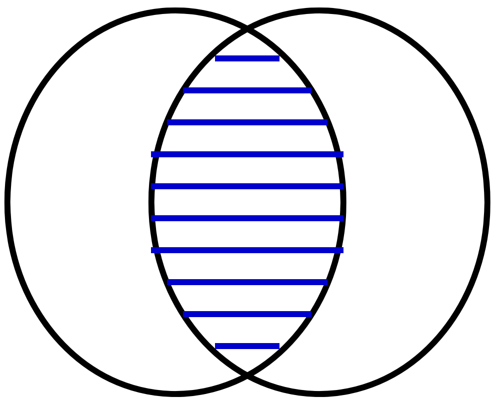
Experimental Surprises at RHIC

- The system thermalizes rapidly
- Hydrodynamic simulations work extremely well and indicate low viscosity (~ 0) (elliptic flow)
- Quarks experience a strong drag force in the "plasma" (elliptic flow, jet-quenching).

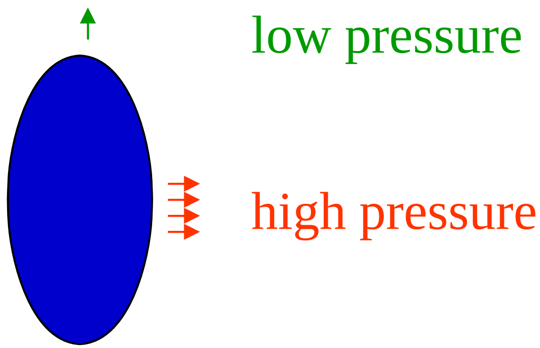
"strongly coupled quark gluon plasma",
"quark gluon liquid"

Elliptic flow.

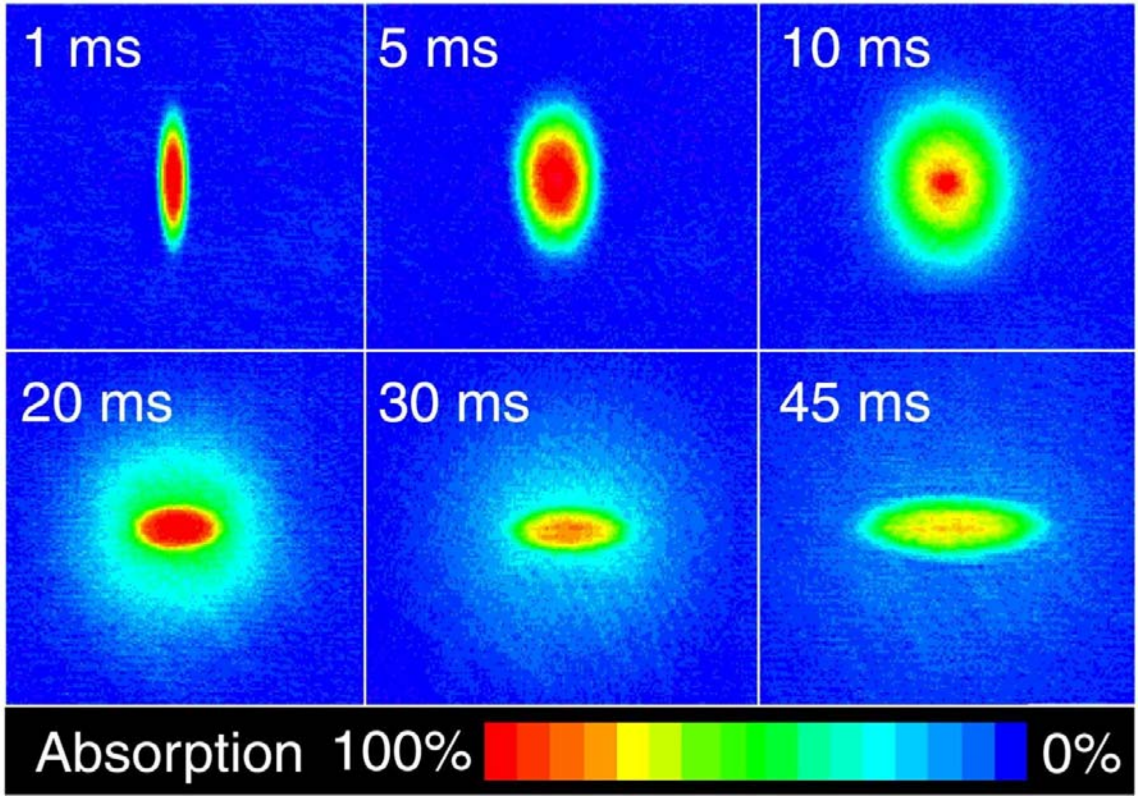




How does the almond shaped fluid expand?



Elliptic flow.



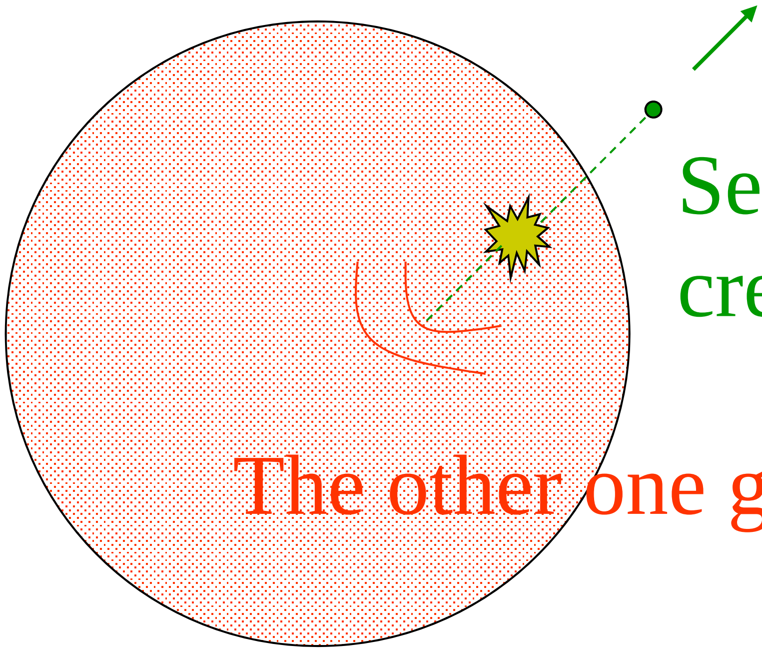
(Cold atomic gas, Ketterle group, MIT)

What do we learn from elliptic flow?

Hydrodynamic modelling works well

- after short thermalization time
- with basically zero viscosity
- for light and heavy quarks (“charm goes with the flow”); implies large drag for heavy quarks

Jet quenching.

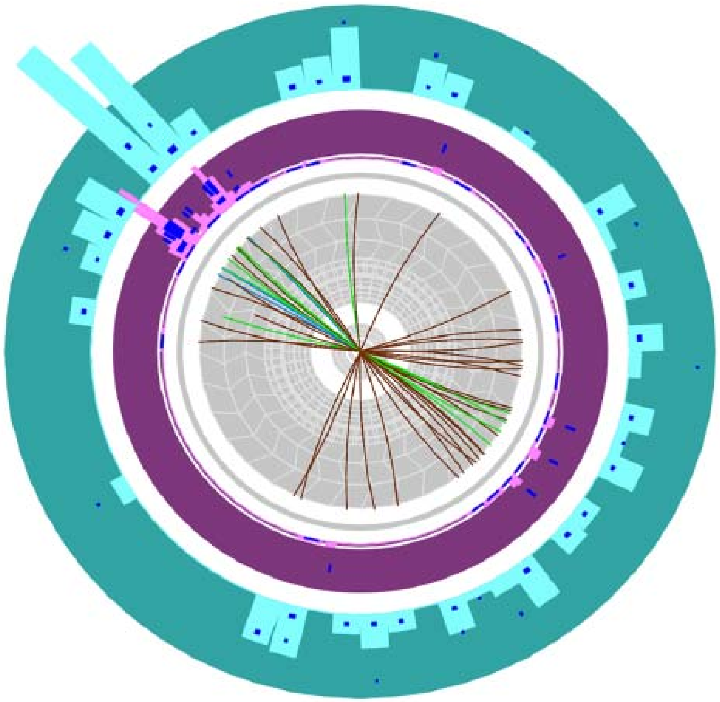


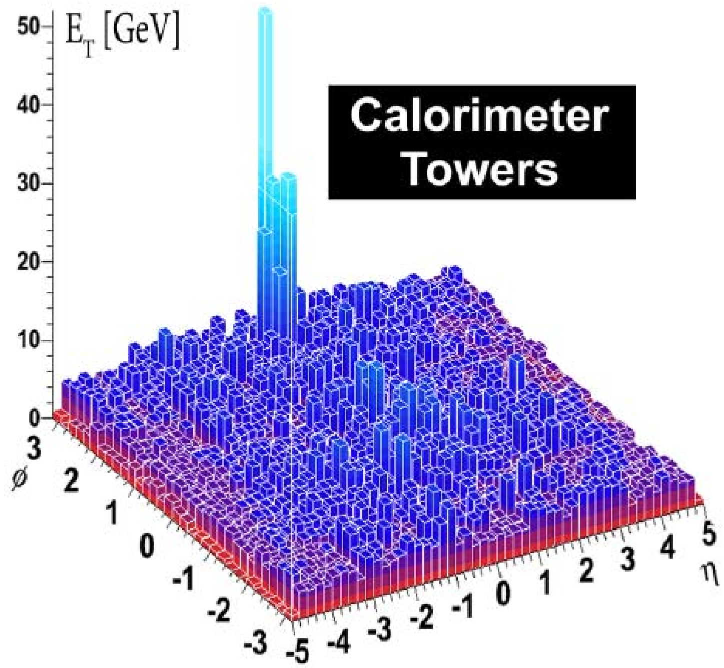
See one of two back-to-back created particles.

The other one got “stuck” in the fireball

Jet quenching is a direct indication of large drag also for light quarks.

Jet Quenching at the LHC (Atlas)





(fist time actually single jet was reconstructed, RHIC only studied 2-particle correlations

Stopping Distance:

For light quarks better question:

How far does quark of energy E travel before it gets thermalized into the plasma?

Perturbative QCD: $L \sim E^{1/2}$ (BDMPS, …)

Experiment: $L \sim E^{1/3}$ gives slightly better fit (Renk, …)

Holography

Can we calculate transport coefficients in *any* strongly coupled field theory?

N=4 SYM at strong 't Hooft coupling!

$$N_c \to \infty \qquad\qquad \lambda = g_{YM}^2 N_c \to \infty$$

AdS/CFT allows us to perform all the microscopic calculations using classical gravity in the 5d dual.
Only known "first principle" calculation of hydro at strong coupling.

What can we learn from N=4 SYM?

It can teach us qualitatively what are typical values of viscosity and drag in a strongly coupled plasma.

N=4 is the only theory in which we can calculate, so we should!

Since hydro is largely insensitive to microscopic details one could hope for some "universality" that all strongly coupled plasmas are the "same" and do quantitative comparisons.

N=4 thermo and hydro.

Thermo: $$s = \frac{3}{4} s_{sb}$$

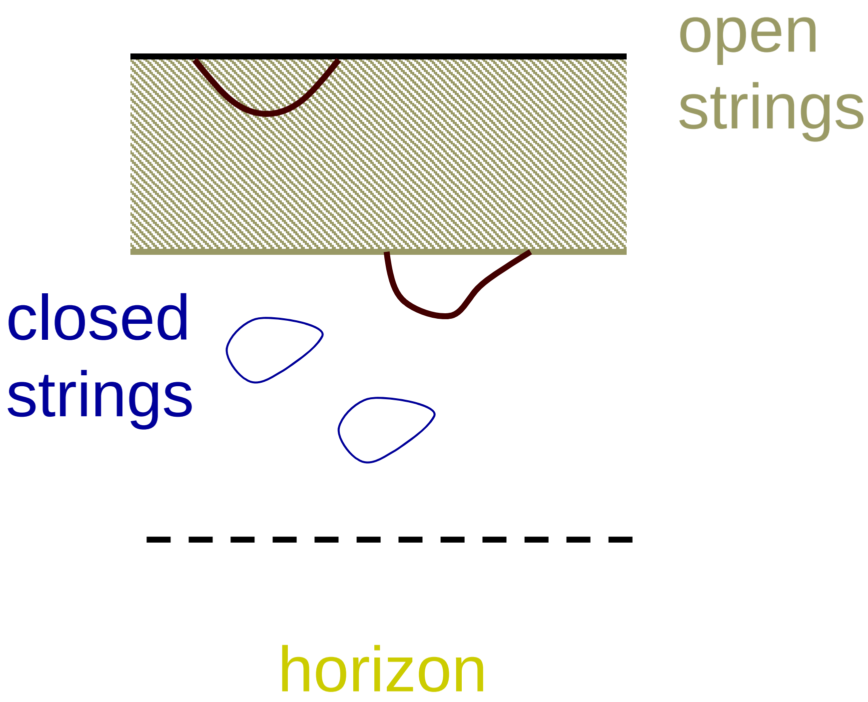
(Gubser, Klebanov, Peet)

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

(Kovtun, Son, Starinets)

Fits data better than 0 but also better than extrapolated PT.

Holographic Quarks.

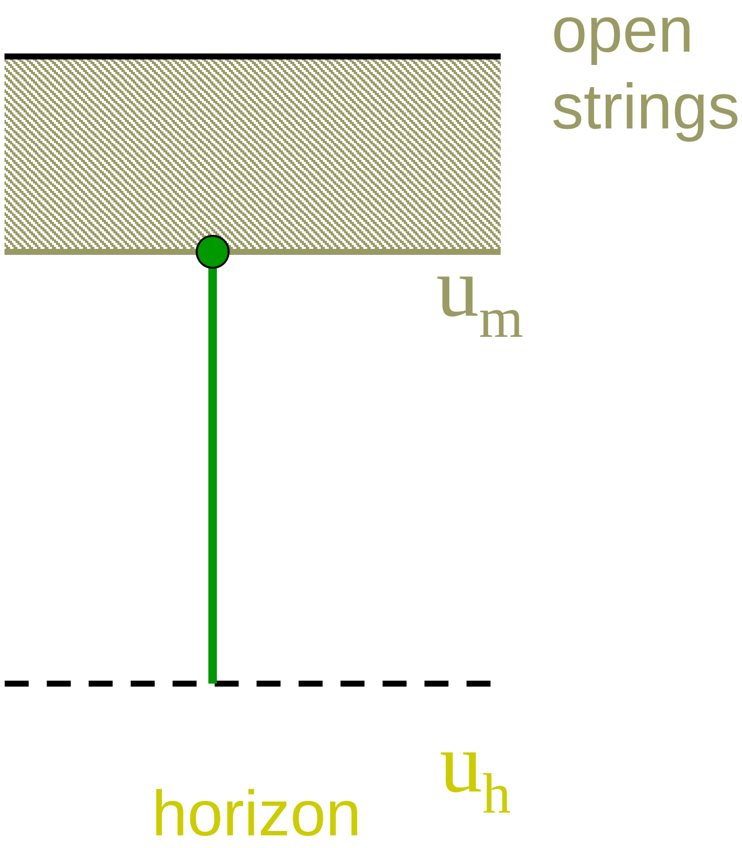


(AK, Ami Katz)

(Sakai, Sugimoto)

- Quarks (N=2 hypers) can be simply incorporate into any background using flavor branes (D7 branes).
- Flavor brane terminates at a position determined by its mass.
- Open strings = Mesons
- Baryons = soliton.

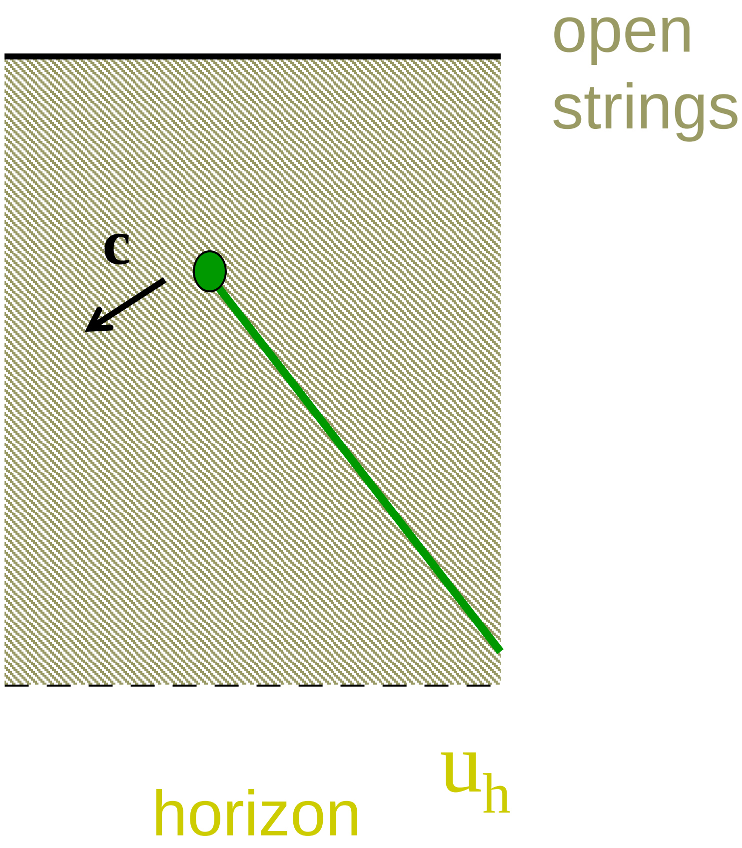
Quarks in N=4 SYM.



- Flavored Quasiparticle can be introduced by semi-classic string.
- Describes Quark and surrounding Plasma cloud.

Mass >> Temperature

Quarks in N=4 SYM.

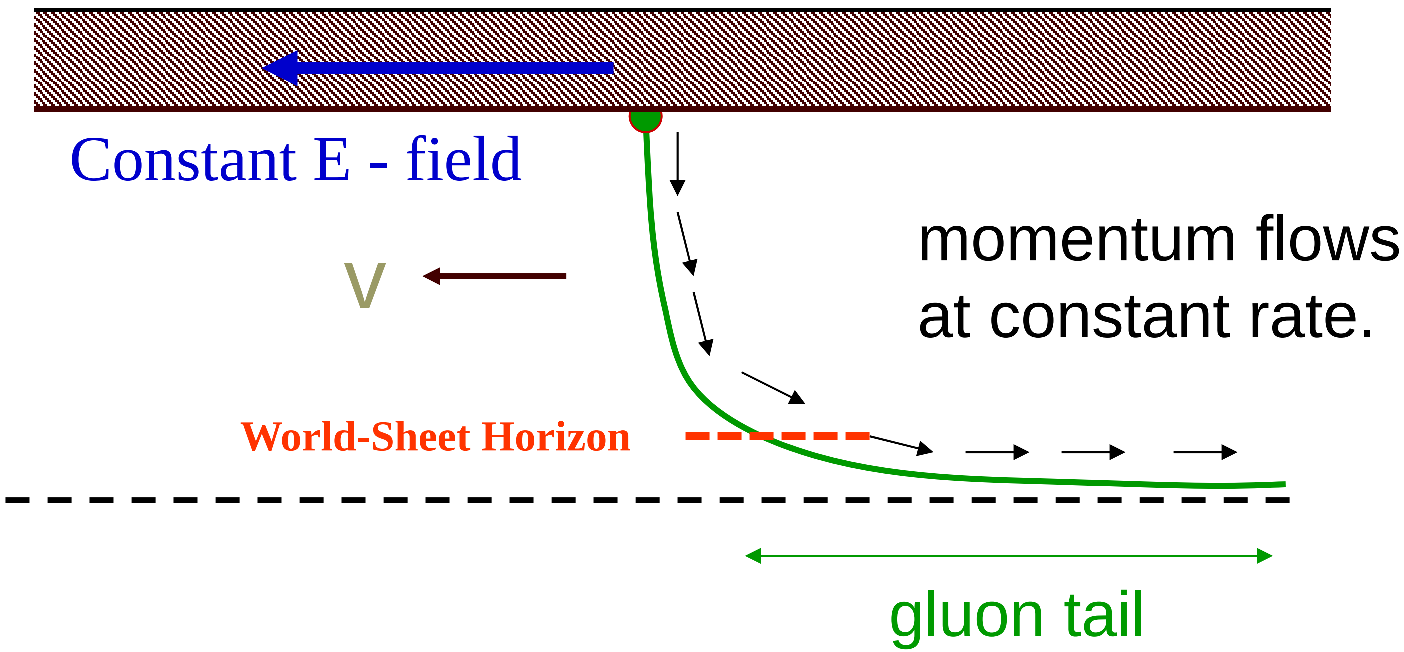


- Flavored Quasiparticle can be introduced by semi-classic string.
- Describes Quark and surrounding Plasma cloud.

Mass << Temperature

Heavy Quark Energy Loss

Drag for a stationary solution. (HKKKY, Gubser)



Loss rate: $$\frac{dP}{dt} = -\frac{\sqrt{\lambda}}{2\pi}\frac{v}{\sqrt{1-v^2}}(\pi T)^2$$

rate at which the external field does work.

Drag for a stationary solution.

Velocity dependece simply from blueshifted energy density.

$\sim\gamma^{2/d}$

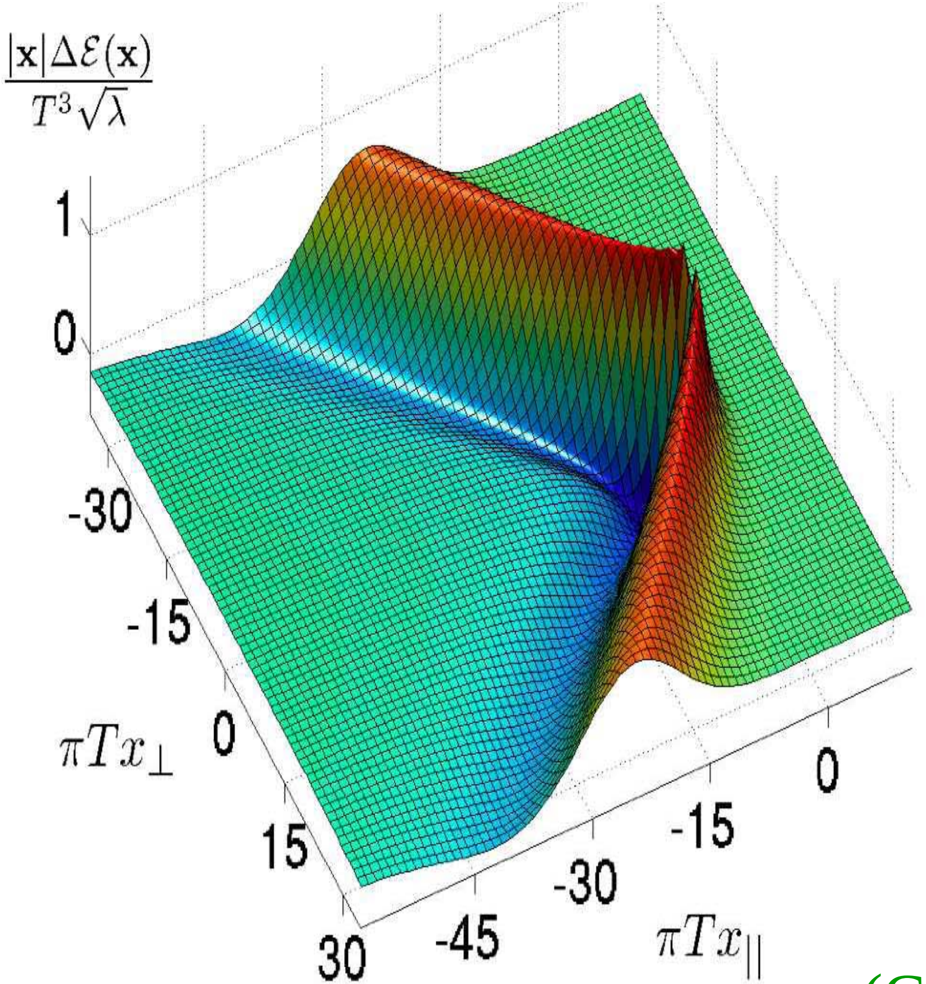
in d dimensions

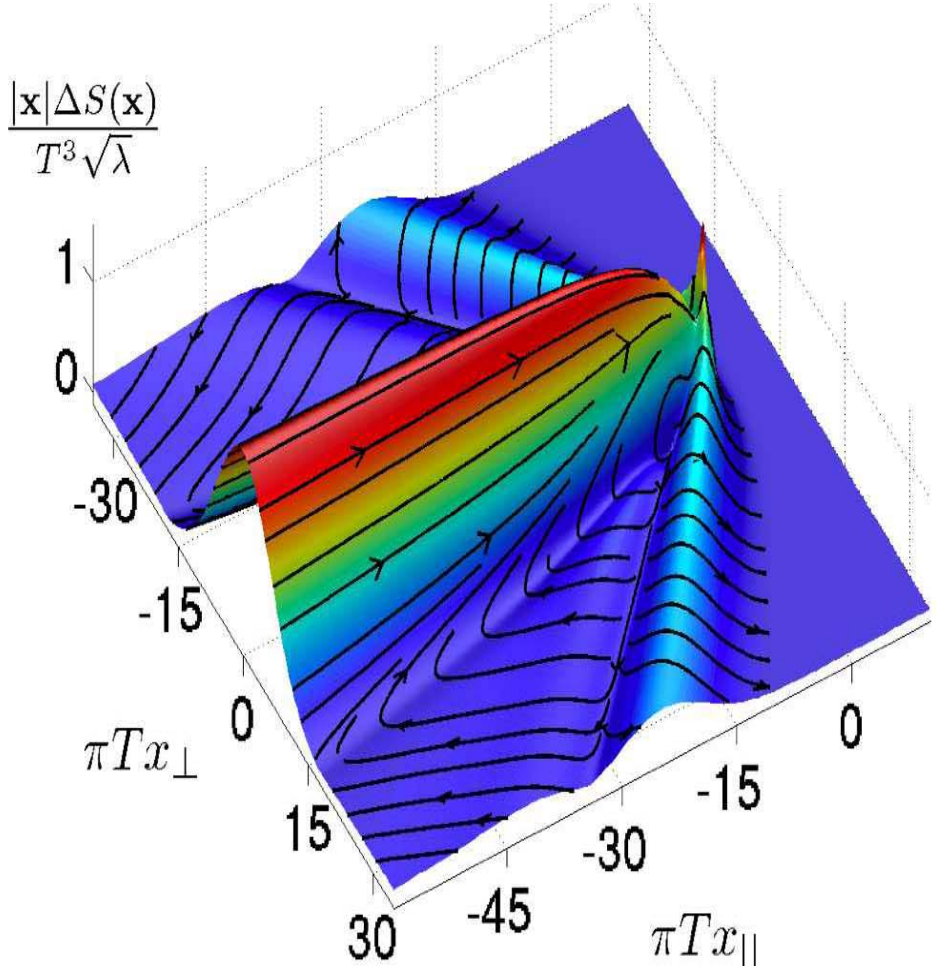
(HKKKY)

Temperature dependence determined by dimensional analysis

Loss rate: $$\frac{dP}{dt} = -\frac{\sqrt{\lambda}}{2\pi}\frac{v}{\sqrt{1-v^2}}(\pi T)^2$$

Energy and Momentum Density





(Chesler and Yaffe)

Small fluctuations:

A lot of extra information in small fluctuations around the dragging string solution:

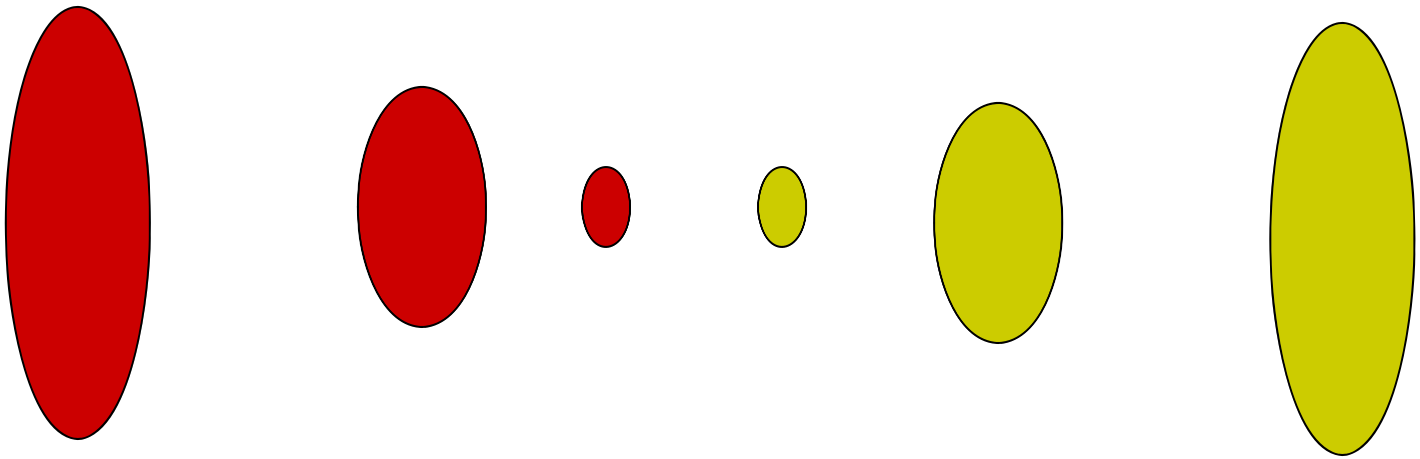
- Relaxation Times
- Momentum Broadening (transverse and longitudinal)
- Brownian Motion = Hawking Radiation
- …..

(HKKKY, ……., Shigemori, …..)

Light Quark Energy Loss

(Chesler, Jensen, Karch, Yaffe)

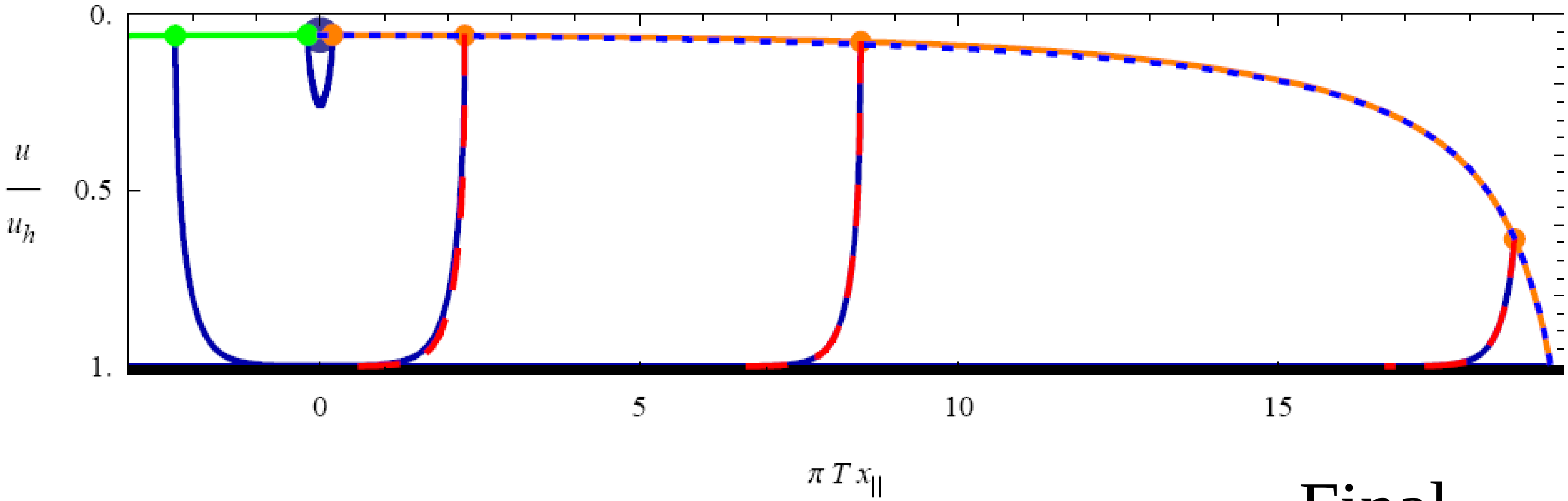
Holographic Image (zero T):



Two “blobs” of energy density / charge density rushing apart and expanding.

“SHOWERING”

Quasi-Particle excitations.

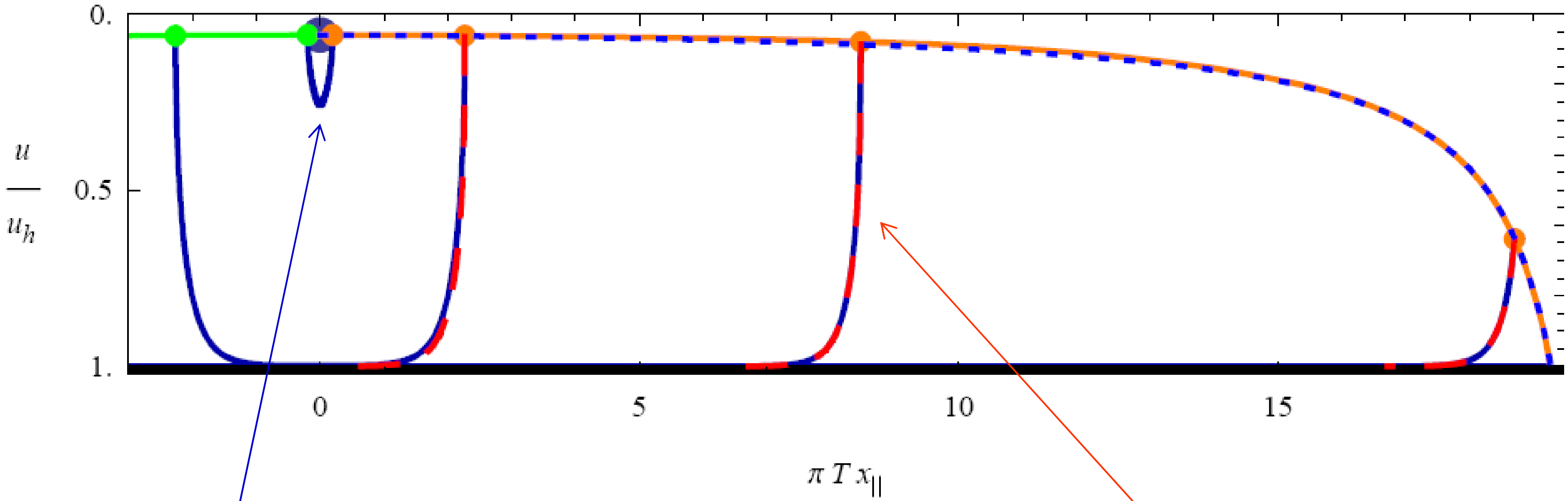


Zero T
Jets

Quasiparticle in Plasma
(for E >> T)

Final
Diffusion

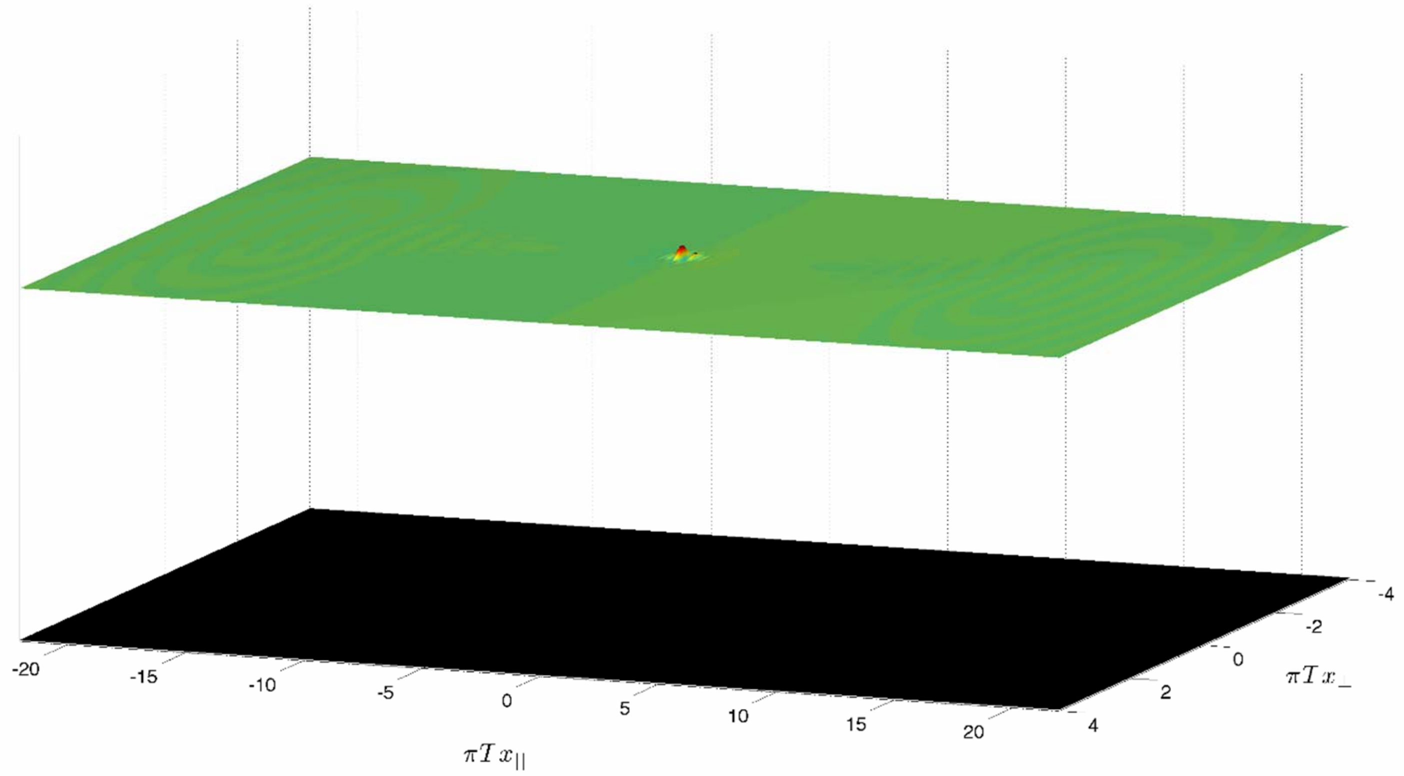
Quasi-Particle excitations.



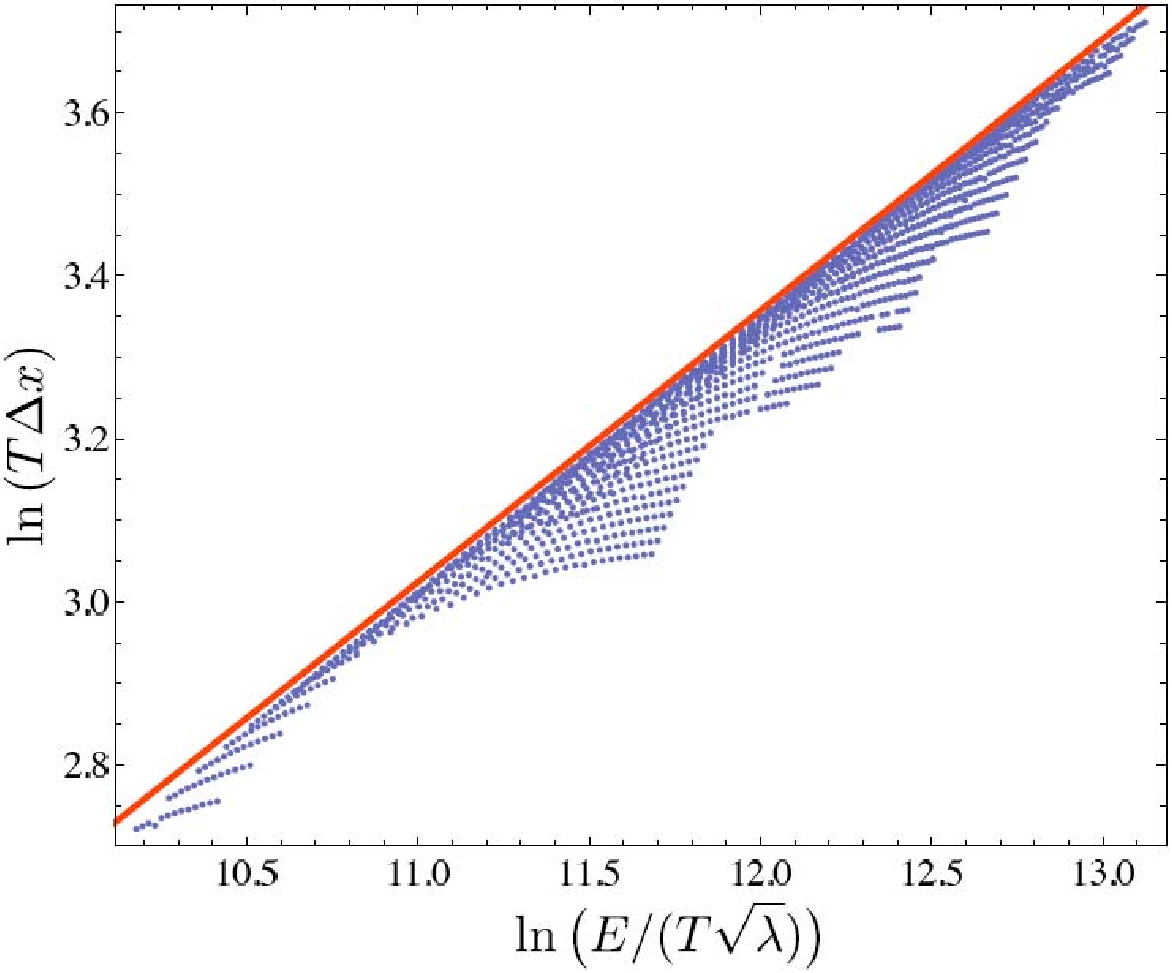
Numeric Solution

Approximate Solution
for E >> T

Jet in N=4 SYM:



Light Quark Stopping Distance



Stopping Distance:

$L_{Max} \sim E^{1/3}$

but strong dependence on details of initial state

Dependence on Initial Data

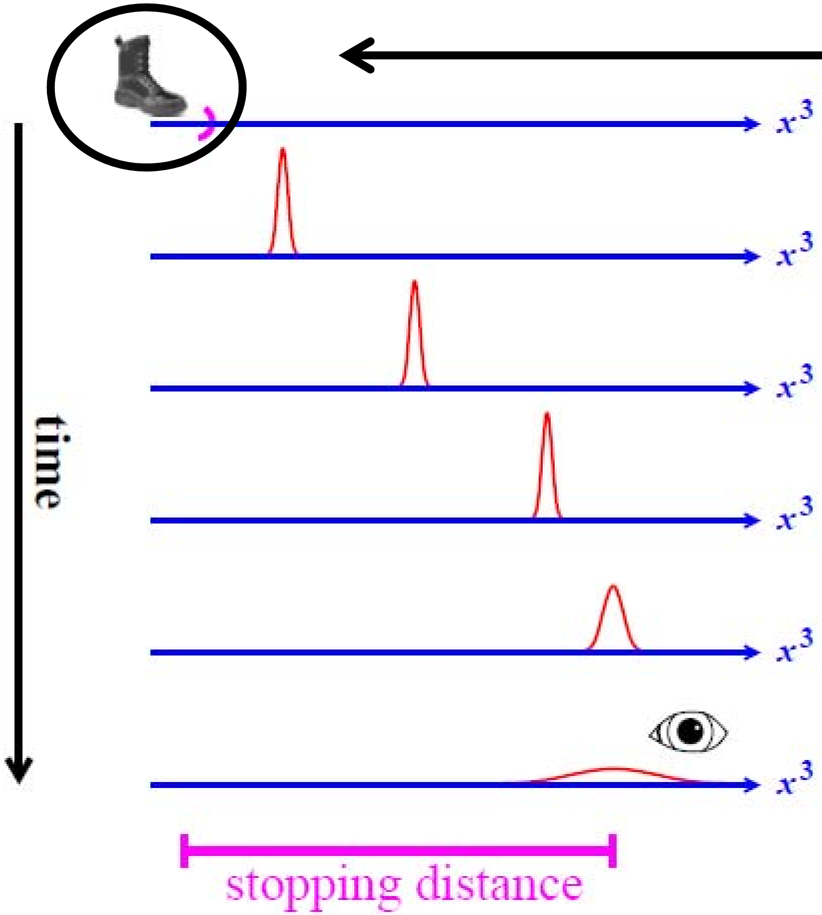
Quasi-Particle = Parton + Soft Gluon Cloud

= Initial Shape of String

Stopping Distance depends on details of gluon cloud!

Need to understand **production mechanism**.

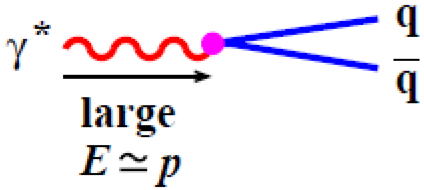
Holographic 3-pt functions (Arnold, Vaman)

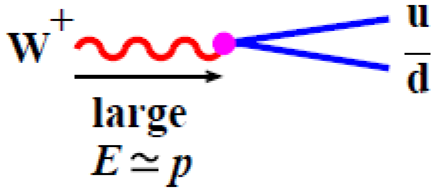


We need to understand better how the quasiparticle was created

Holographic 3-pt functions (Arnold, Vaman)

In the real world:





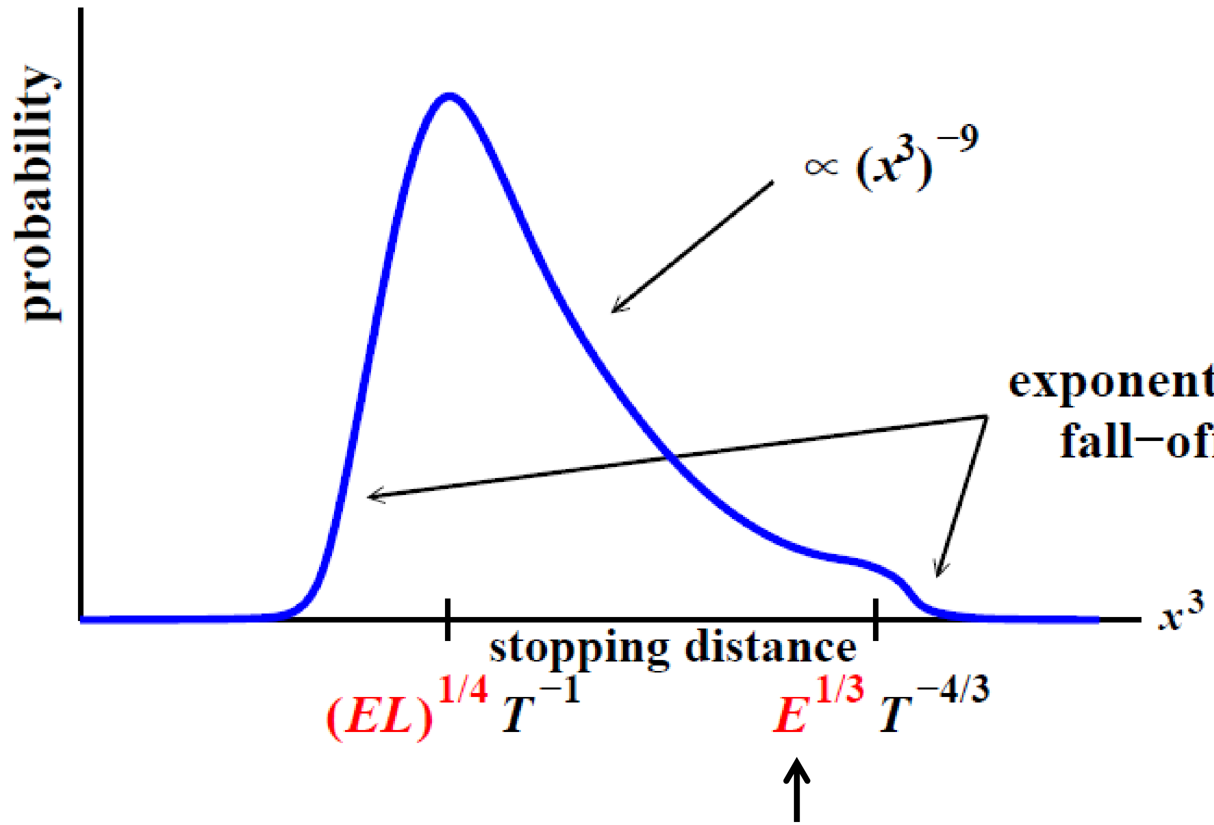
Formally:

$|\,\mathrm{jet}\rangle$ =  $|\,\mathrm{plasma}\rangle$

$\langle\mathrm{jet}\,|$  $|\,\mathrm{jet}\rangle$ = $\langle$  †   $\rangle$

Thermal 3-pt function
(can be done holographically)

Stopping distance

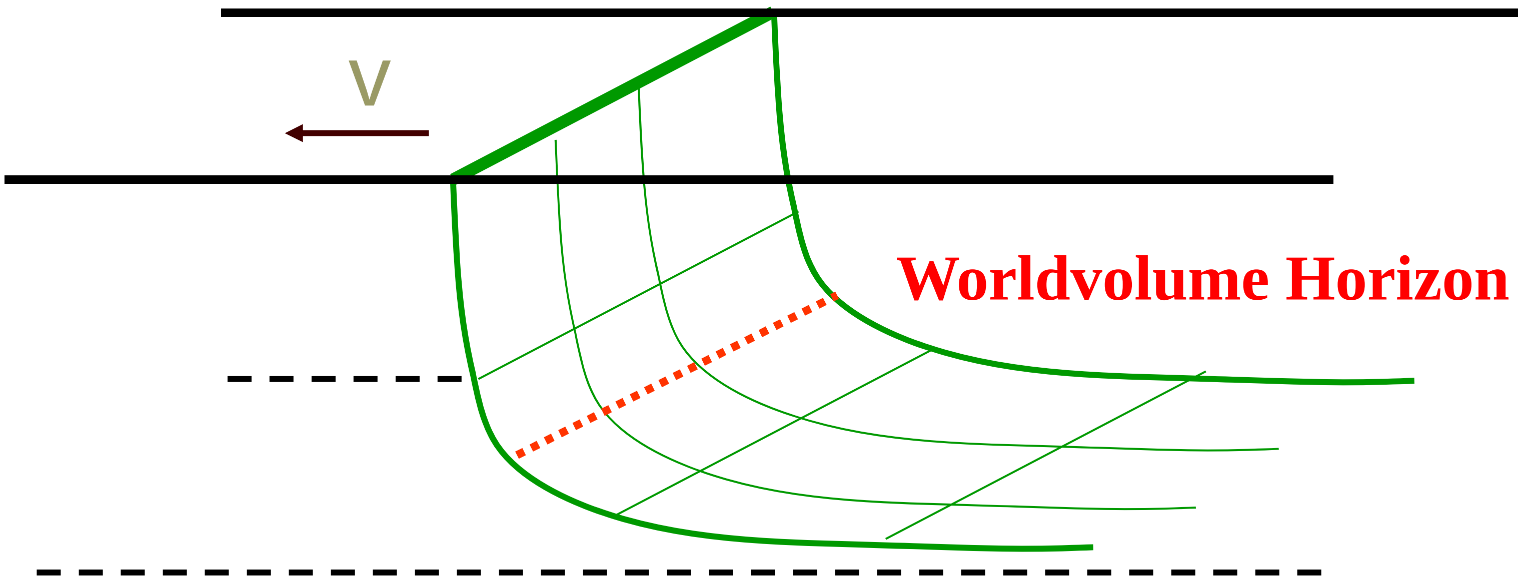


Experiment?

agrees with us on maximal stopping distance

Dragging Sheets

Dragging Sheets (Janiszewski and Karch)



Only sensitive to blue-shifted energy density?
Inhomogeneities?

Loss Rate:

n: spatial dimensions of defect
d: space-time dimensions of the field theory

$$\frac{\textbf{Energy}}{\textbf{(time * volume)}} = T_0 R^{n+2} \left(\frac{4\pi}{d}\right)^{n+2} v^2 T_{eff}^{n+2}$$

Only sees blueshifted density! $\quad T_{eff} \equiv \gamma^{2/d} T.$

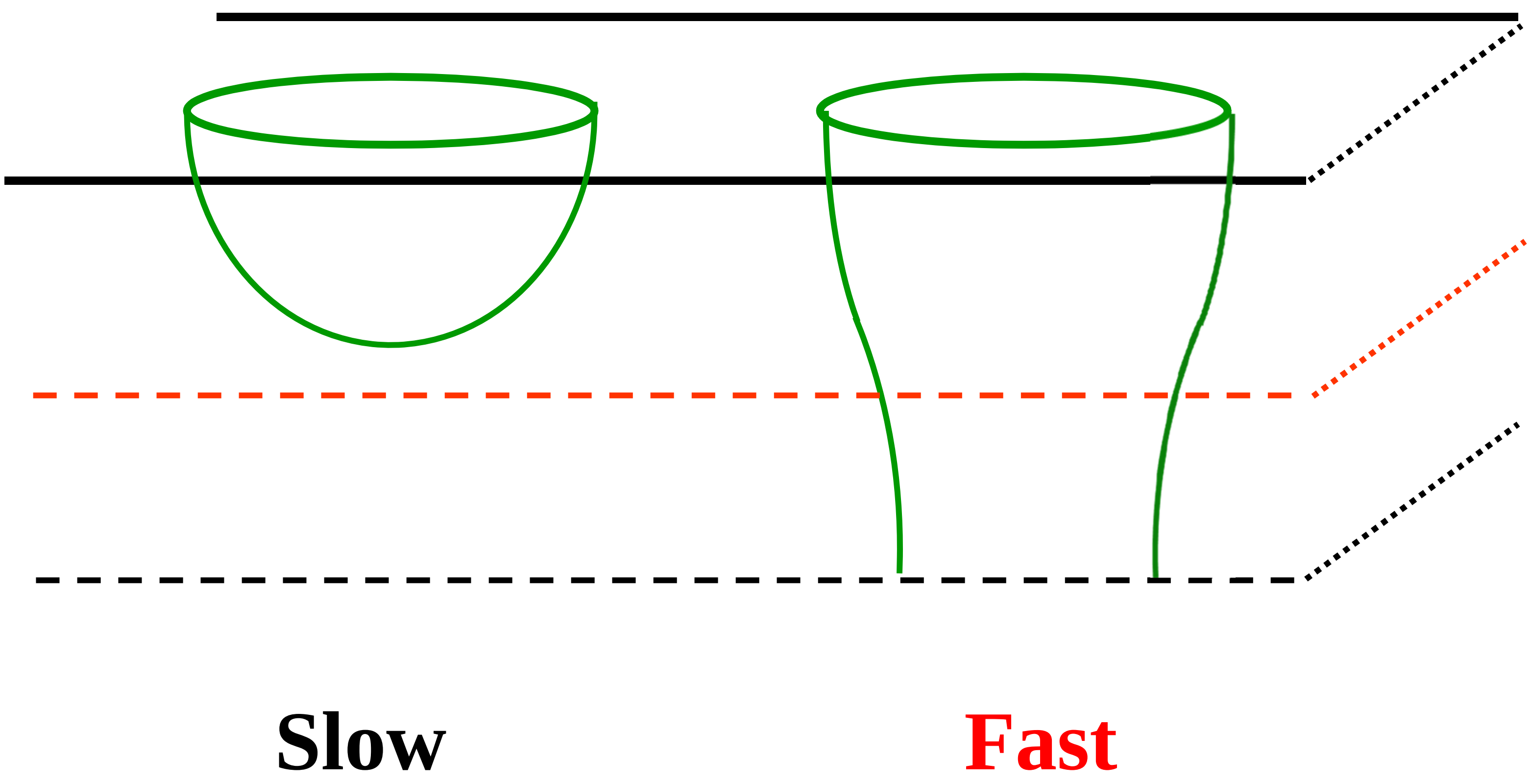
Induced Horizons.

Moving defects induce worldvolume horizons even in the absence of spacetime horizons.

(see also Das, Nishioka, Takayanagi and Frolov, Mukohyama)

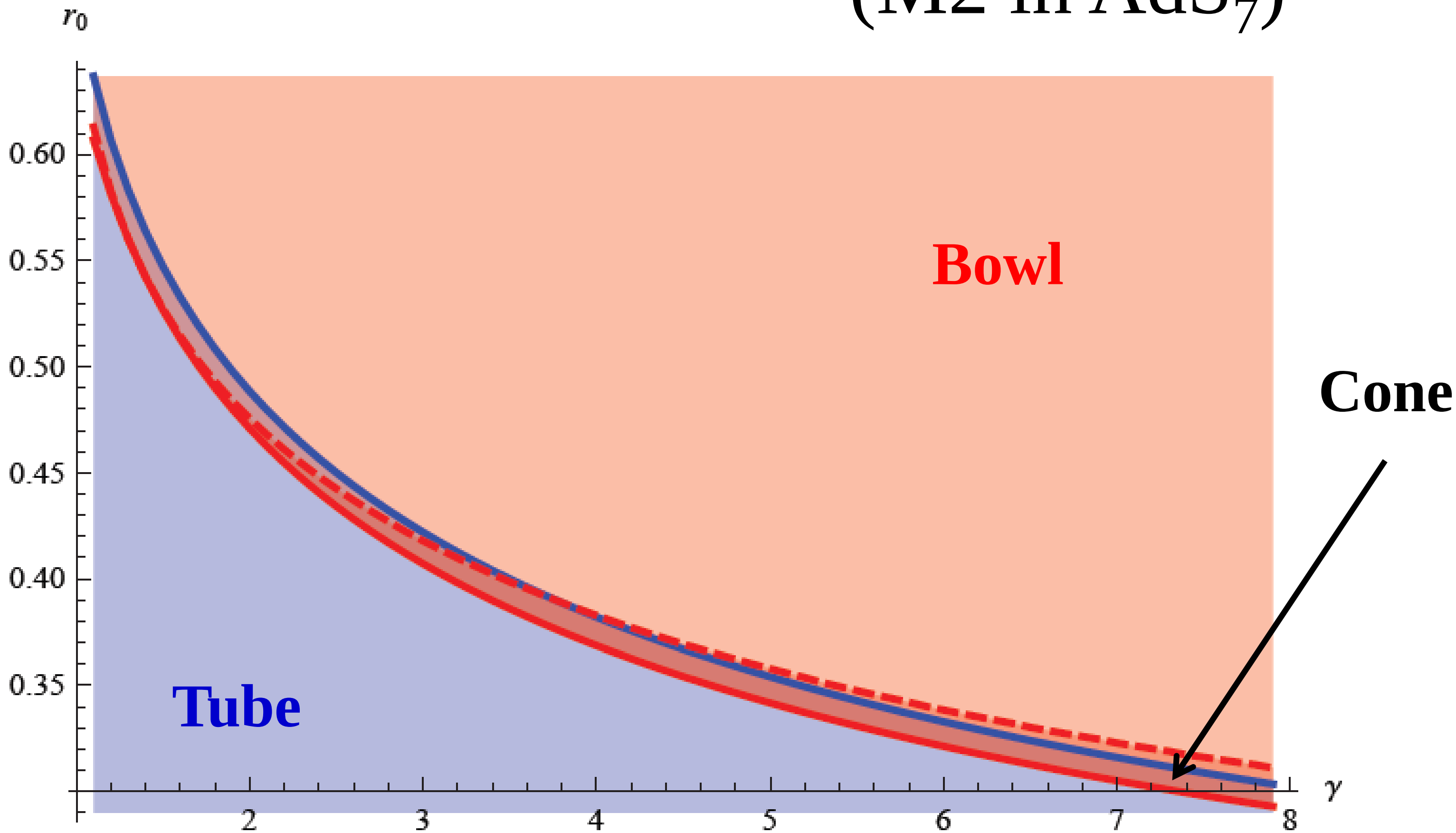
Higher dimensional defects allow more interesting induced gravitational phenomena.

World-volume Hawking-Page

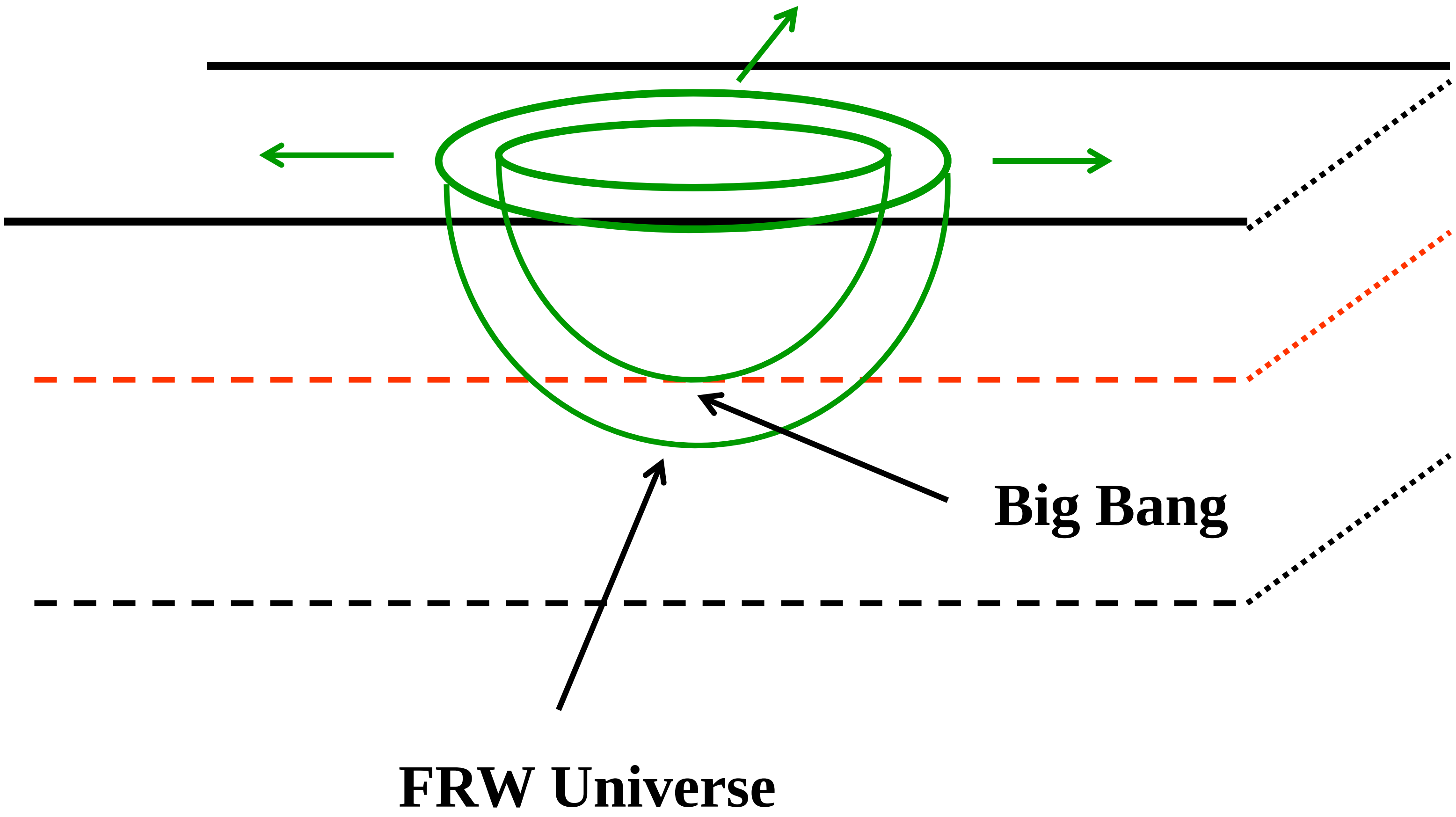


World-volume Hawking-Page

(M2 in AdS$_7$)



World-volume FRW Universe



Conclusion (1/2)

Holography provides solvable toy models of strong coupling dynamics.

Energy Loss qualitatively different from weak coupling.

Conclusion (2/2)

By studying higher dimensional defects we can:

- confirm the lack of structure in strongly coupled energy loss
- produce tractable world-volume analogs of curved spacetimes with horizons

Next: Fluctuations? Turbulence?