AdS/CFT and Heavy Ion Collisions at RHIC and LHC

Hong Liu

Massachusetts Institute of Technology

(New) Adventures in QCD

QCD has presented us many fascinating dynamical phenomena:

Confinement,
chiral symmetry breaking,
asymptotic freedom,
internal structure of nucleons
……

largely guided by experiments, great challenges for theorists.

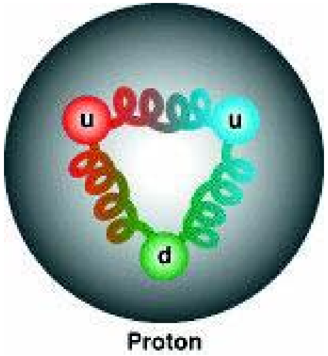
Recently, heavy ion collision experiments opened new frontiers into probing dynamical phenomena in QCD:

many body physics,
collective phenomena,
finite temperature,
……

Quark-Gluon Plasma

At room temperature, quarks and gluons are always confined inside colorless objects (hadrons):

protons, neutrons, pions, …..

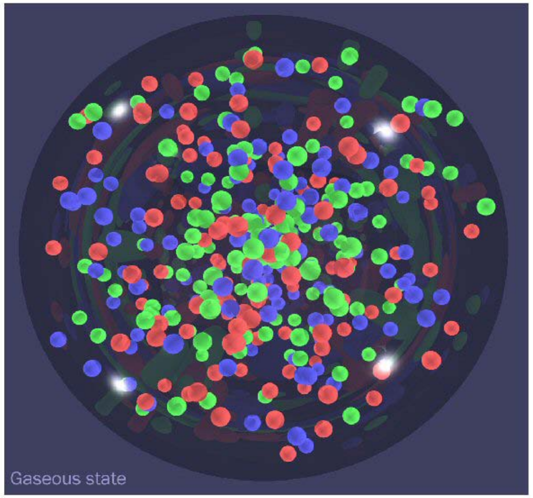


Very high temperature (e.g. 1 TeV):

→ Interactions become weak

→ quarks and gluons deconfined

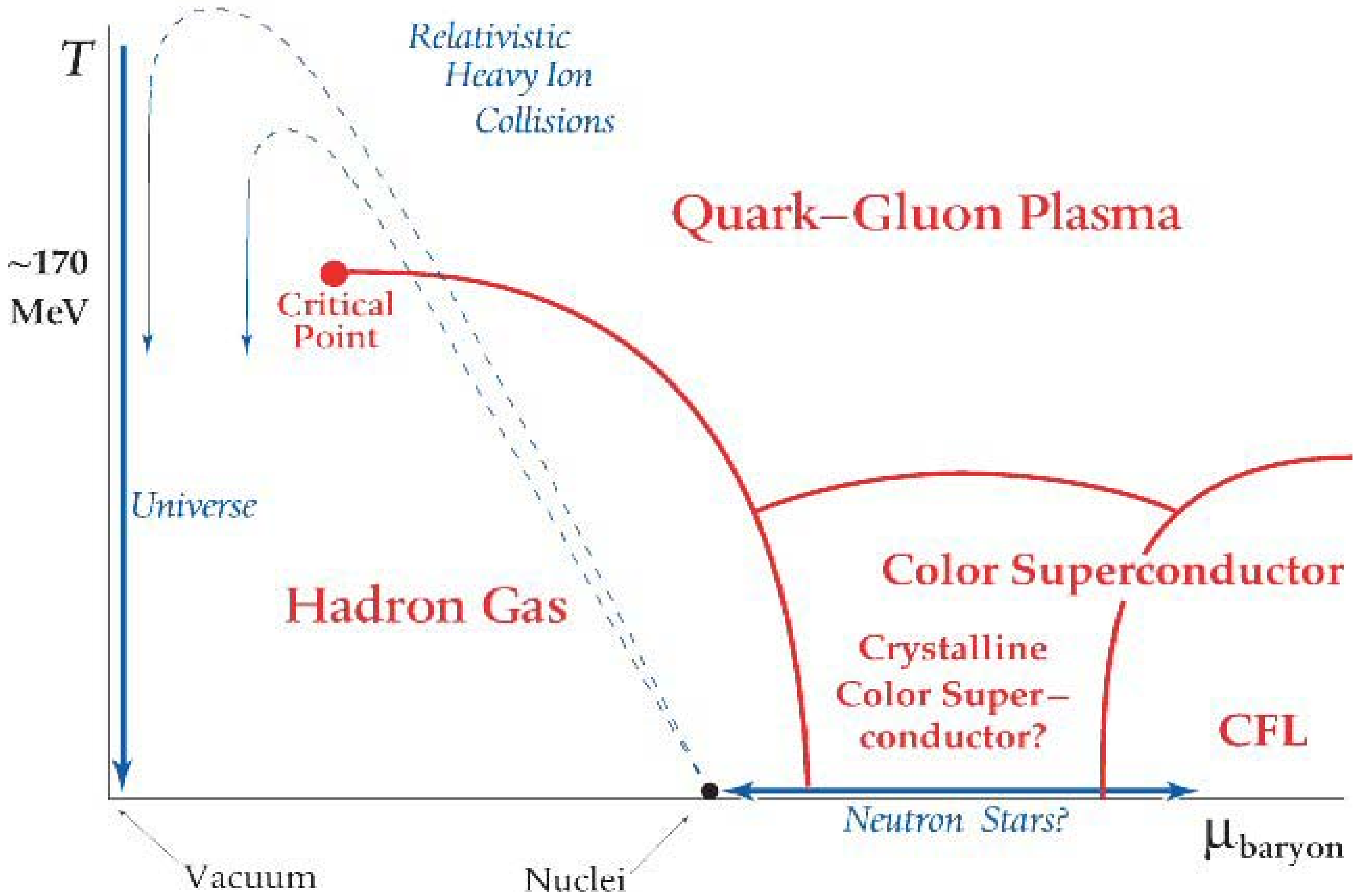
→ Quark-gluon plasma (QGP)



Infinitely high temperature:

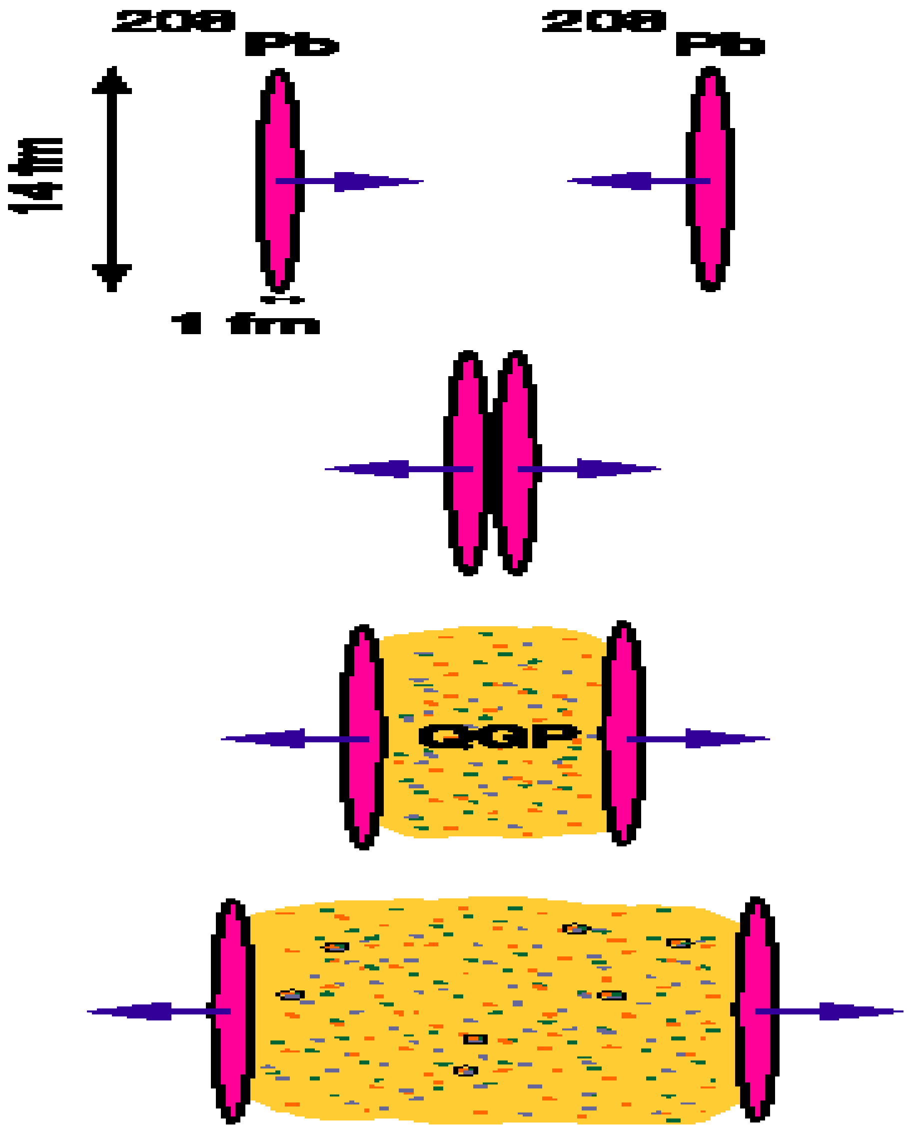
QGP behaves like an ideal gas.

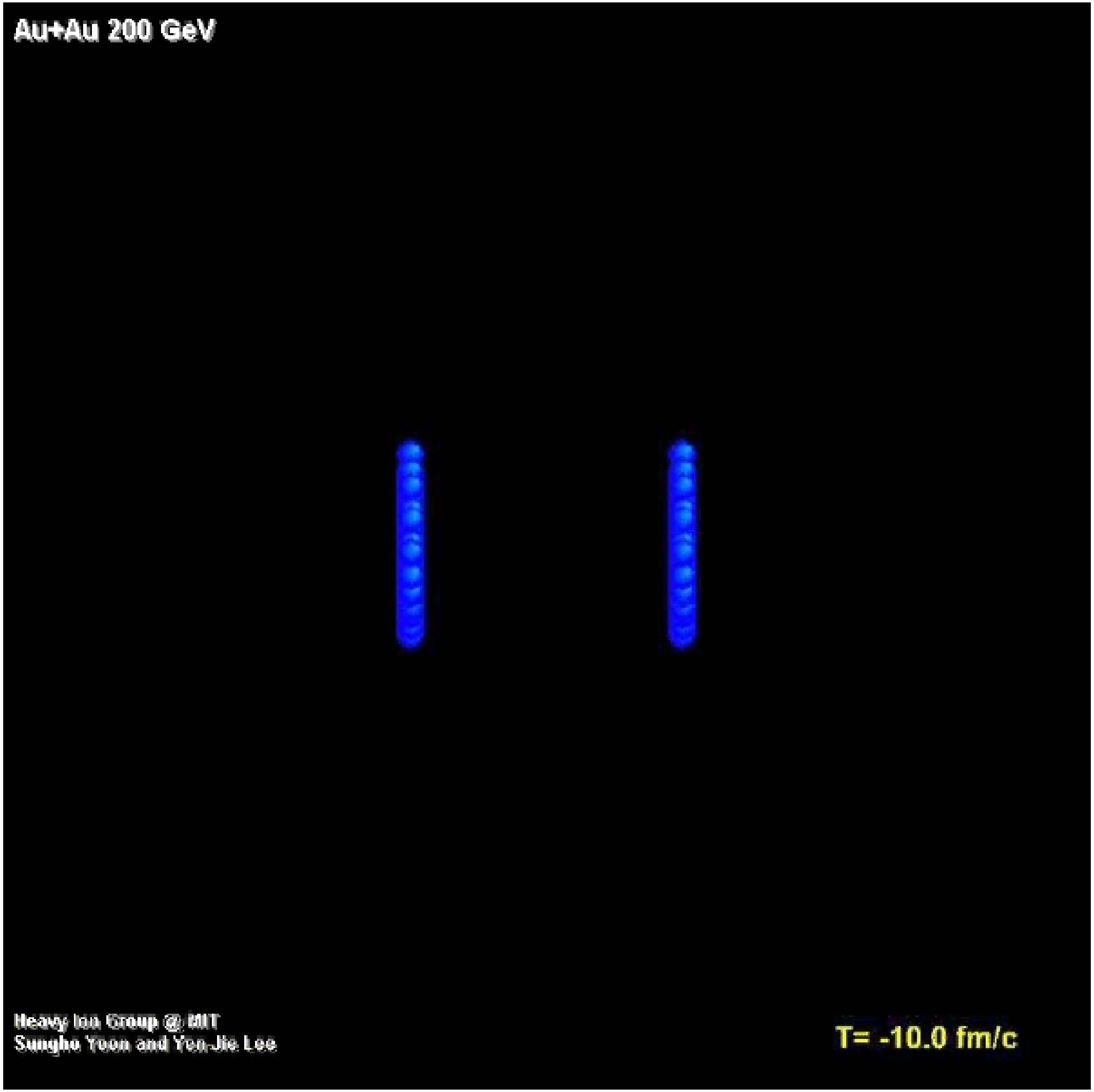
EXPLORING *the* PHASES *of* QCD



Small baryon density : Smooth crossover at $T_C \sim 170$ MeV

Relativistic Heavy ion collisions




Au+Au 200 GeV
Heavy Ion Group @ MIT
Sungho Yoon and Yen-Jie Lee
T= -10.0 fm/c

Relativistic heavy ion collisions

RHIC (2000): Au+Au $\sqrt{s_{NN}} = 200\,GeV$

$\sqrt{s_{NN}}$: center of mass energy per pair of nucleons

Au: 197 nucleons; Total: 39.4 TeV

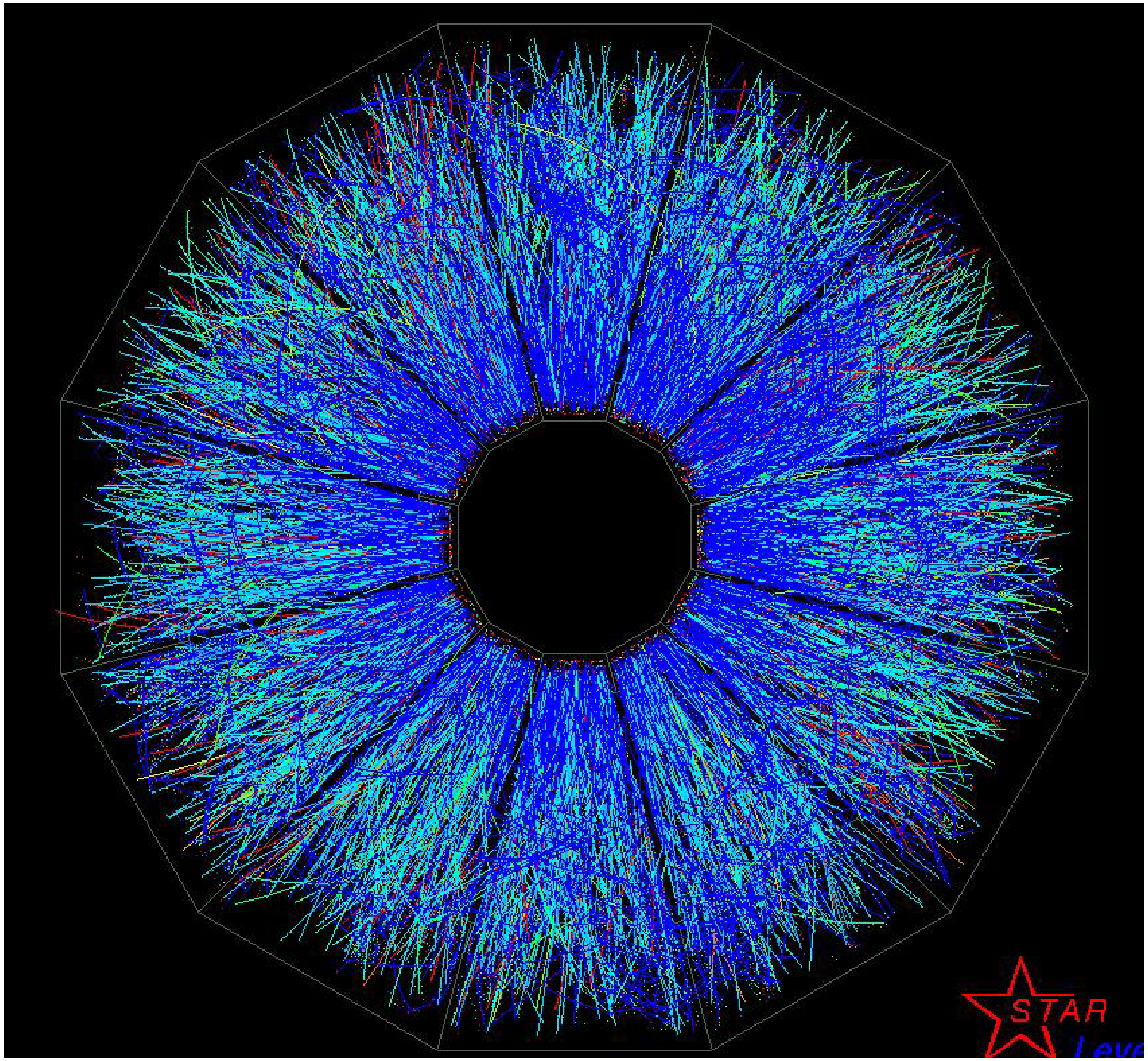
Temperature (1 fm after collision) ~ 250 MeV

Baryon chemical potential ~ 27 MeV

Deconfinement crossover in QCD: T_C ~ 170 MeV

LHC: Pb + Pb (2009) $\sqrt{s_{NN}} = 5{,}500\,GeV$

Enormous experimental challenges !



Observables of RHIC QGP

Probes of the QGP:

- Thermodynamic properties
- Collective flow
- Jet quenching (parton energy loss)
- Quarkonium suppression

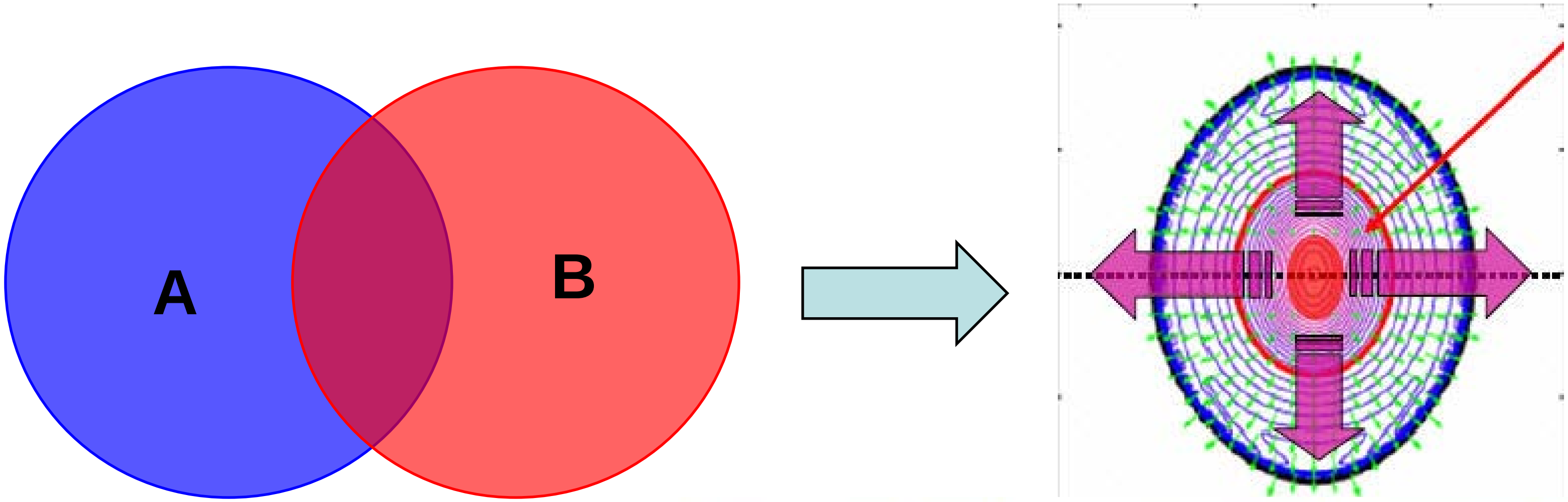
....

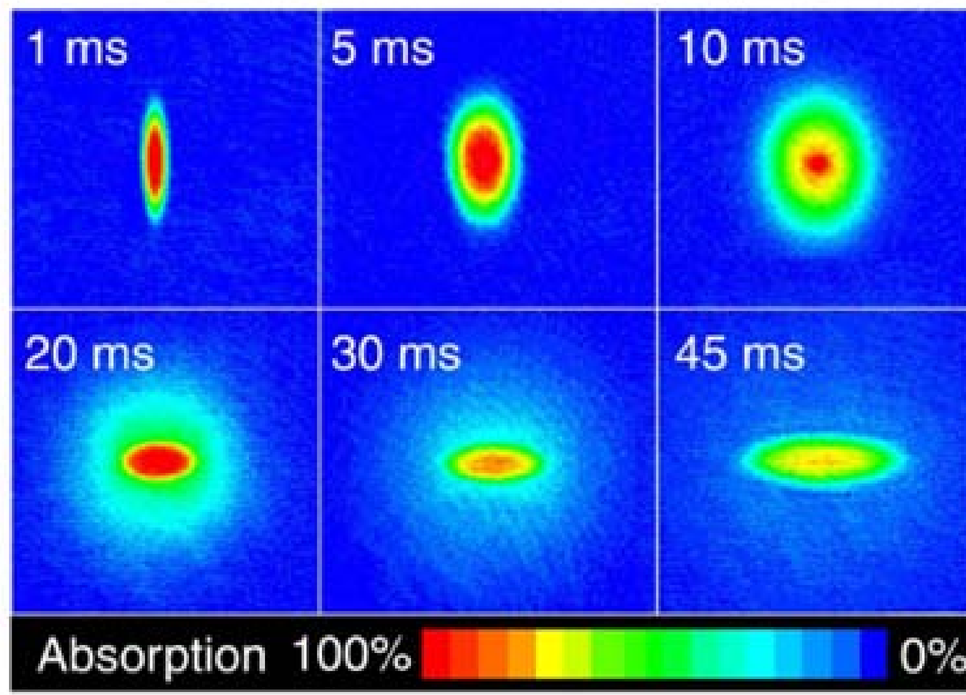
RHIC QGP:

behaves very differently from a weakly coupled QGP gas

(Perturbation theory: inadequate)

Collective Flow





Na_{23}

Bose condensate

Ketterle group, MIT

Collective flow and shear viscosity

Match hydrodynamics simulation with data

RHIC QGP: $$\frac{\text{shear viscosity}}{\text{entropy density}} \equiv \frac{\eta}{s} < O(0.1)$$

$$\frac{\eta}{s} \sim O(1)$$ (perturbative QCD)

Water $$\frac{\eta}{s} \sim 10$$

RHIC QGP:

$$\boxed{\text{strongly coupled, liquid-like (nearly ideal)}}$$

exciting opportunities, but difficult challenges

String theory to the rescue!

AdS/CFT techniques have potential to make important impacts !

1. Search string (gravity) duals for QCD

2. Use strongly coupled $\mathcal{N}=4$ SYM plasma or its relatives as benchmarks for understanding the QCD QGP.

Can $\mathcal{N}=4$ SYM plasma serve as an ``Ising model'' for QCD QGP?

finite temperature helps!

$\mathcal{N}$=4 SYM v.s. QCD

$\mathcal{N}$=4 SYM at finite T	QCD at T ~T_C -3 T_C
• conformal	• near conformal (lattice)
• no asymptotic freedom, no confinement	• not intrinsic properties of sQGP
• supersymmetric (badly broken)	• not present
• no chiral condensate	• not present
• no dynamical quarks, 6 scalars and 4 fermions in the adjoint representation.	• may be taken care of by proper normalization

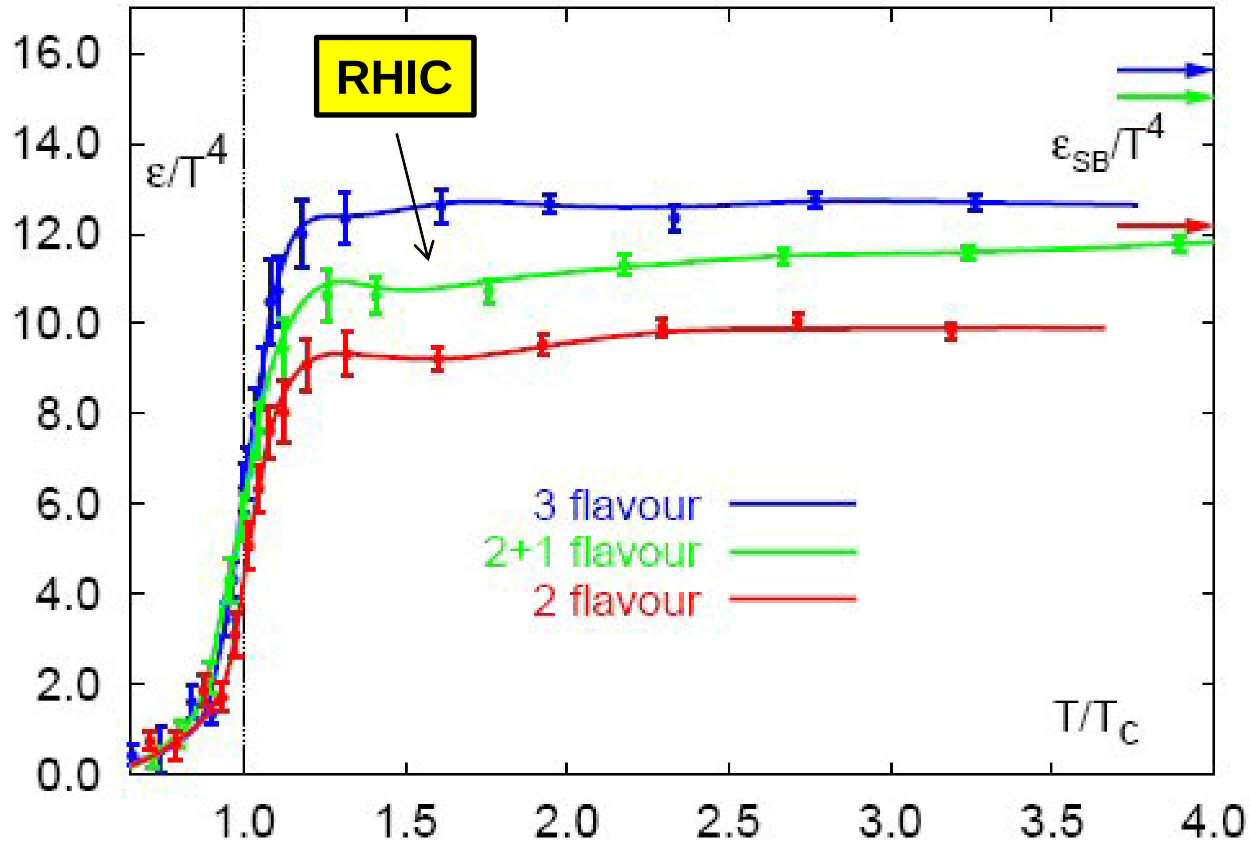
Purpose of the talk

Describe various dynamical insights obtained from AdS/CFT into some most important observables of heavy ion collisions

- Thermodynamic properties
- Shear viscosity
- Jet quenching (parton energy loss)
- Quarkonium suppression
  (a prediction from string theory)

Thermodynamics

QCD:



Karsch
hep-lat/0106019

Weak dependence on T of ε / T^4 in the range $T_C \sim 4\,T_C$

approximately scale invariant

$$\frac{\varepsilon(\text{a few } T_C)}{\varepsilon(\infty)} \approx 0.8$$

(In)famous 3/4

$\mathcal{N}$=4 SYM: Gubser, Klebanov, Peet

$$\frac{\varepsilon_{\lambda=\infty}}{\varepsilon_{\lambda=0}} = \frac{S_{\lambda=\infty}}{S_{\lambda=0}} = \frac{P_{\lambda=\infty}}{P_{\lambda=0}} = \frac{3}{4}$$

Thermodynamics of very weakly and very strongly coupled plasmas can be similar.

Infinite families of gauge theories (with different gauge groups and matter contents) share similar properties: Nishioka, Takayanagi

$$\frac{S_{\lambda=\infty}}{S_{\lambda=0}} = \frac{3}{4} f, \quad .89 \leq f \leq 1.2$$

QCD v.s. $\mathcal{N}$=4

QCD: $$\frac{\varepsilon(\text{a few } T_C)}{\varepsilon(\infty)} \approx 0.8$$

$$0.8 = \frac{3}{4} \times 1.06$$

Shear viscosity

QCD: $$\frac{\eta}{s} < O(0.1)$$

$\mathcal{N}$=4 SYM:

$$\frac{\eta}{s} = \frac{1}{4\pi} \approx 0.08$$

Policastro, Son, and Starinets

This ratio is in fact universal For all known strongly coupled QGPs with a gravity description:

Kovtun, Son and Starinets
Buchel, J. Liu

Conformal or not, supersymmetric or not,
chemical potential or not, confining at T=0 or not,
having fundamentals or not
with varying number of degrees of freedom

Universality ?

We now know infinite classes of different QGPs:

similar thermodynamical properties

universality of shear viscosity

Is QCD at T~ a few T_C in this class?

To what observables does the universality apply ?

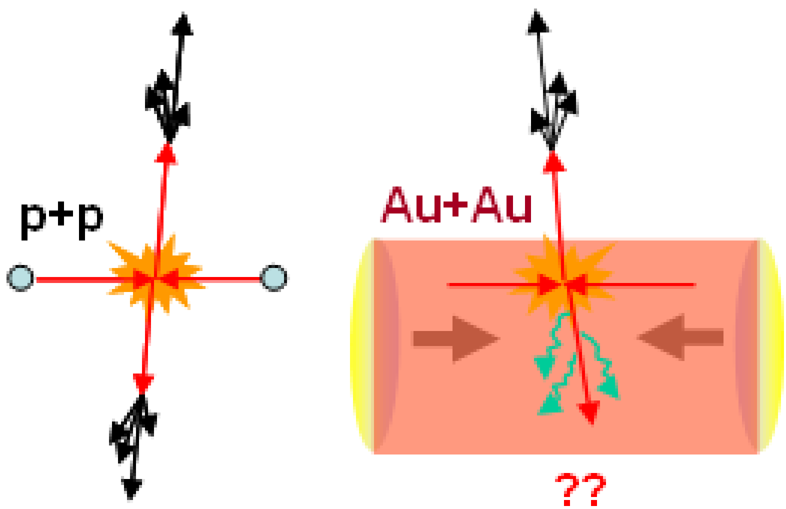
A prediction from string theory

Heavy quarkonia as probes of QGP

A hallmark of QGP is that it screens color objects.

The potential between the quark and anti-quark in a quarkonium bound state is sensitive to the screening of the plasma.

They dissociate at $T_d > T_C$



Heavy ion collisions: color screening in the produced medium

J/ψ suppression

Matsui and Satz (1987)

Screening in a QGP

V(L): potential between a Q and Qbar

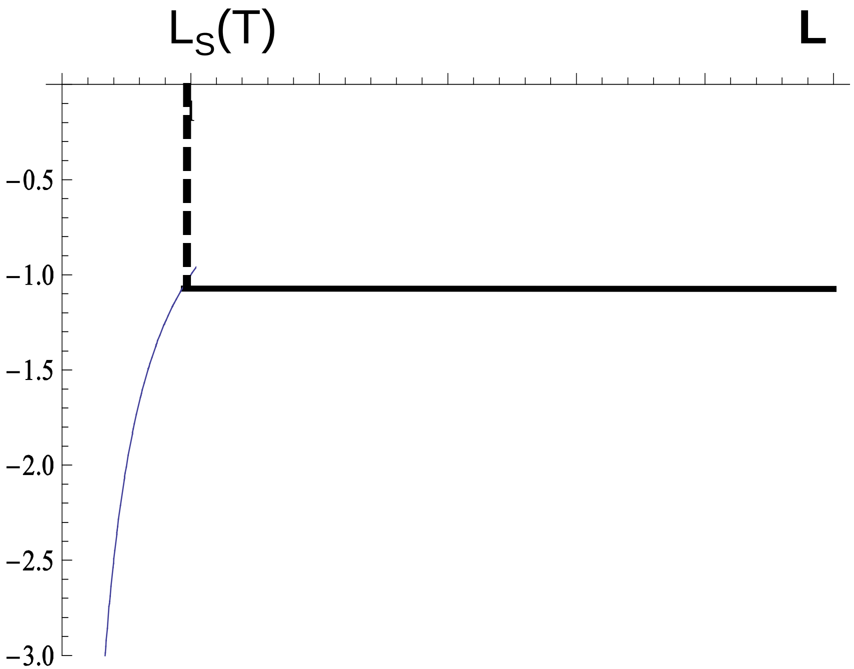
$$T = 0: \quad V(L) \sim \frac{1}{L}$$

$\mathcal{N}$=4 SYM:

$$L_S(T) = \frac{0.277}{T}$$

QCD above T_C

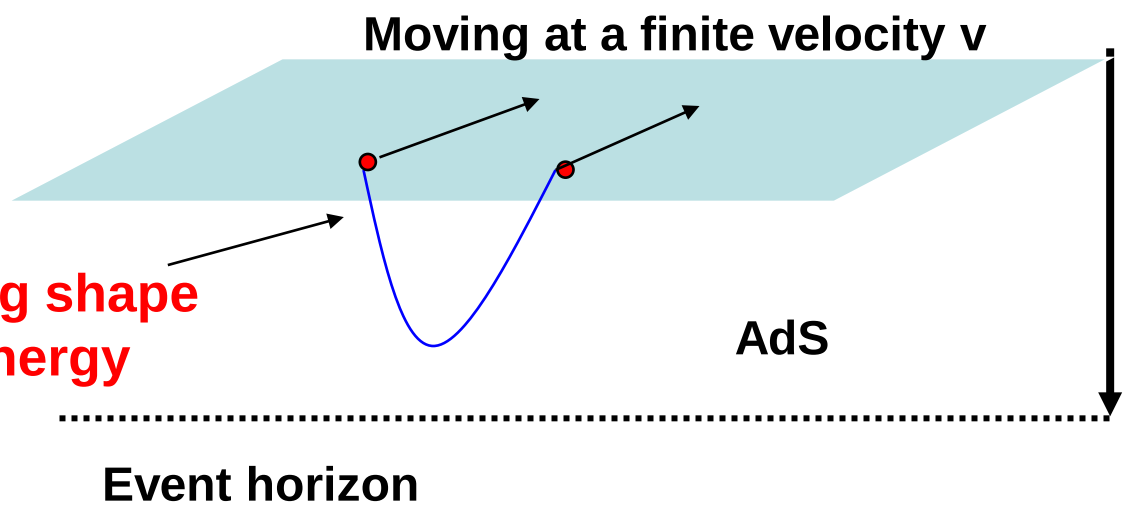
$$L_S \sim 0.5 / T$$



Finite velocity scaling

Heavy ion collisions: Q and Qbar move relative to the plasma

screening at finite velocity ?   (not known)



Finding string shape of minimal energy

HL,Rajagopal,Wiedemann

$$L_S(\mathrm{v}) \sim L_S(0)(1-\mathrm{v}^2)^{1/4} \sim (1-\mathrm{v}^2)^{1/4}\,\frac{1}{T}$$

Chernicoff, Garcia, Guijosa

Peeters, Sonnenschein, Zamaklar

I will now assume a similar scaling applies to QCD

$$L_S(\mathrm{v}) \sim L_S(0)(1-\mathrm{v}^2)^{1/4} \sim (1-\mathrm{v}^2)^{1/4}\frac{1}{T}$$

$\Rightarrow$ **Bound states are more unstable at large Momenta.**

This effect could lead to significant suppression at large P_T.

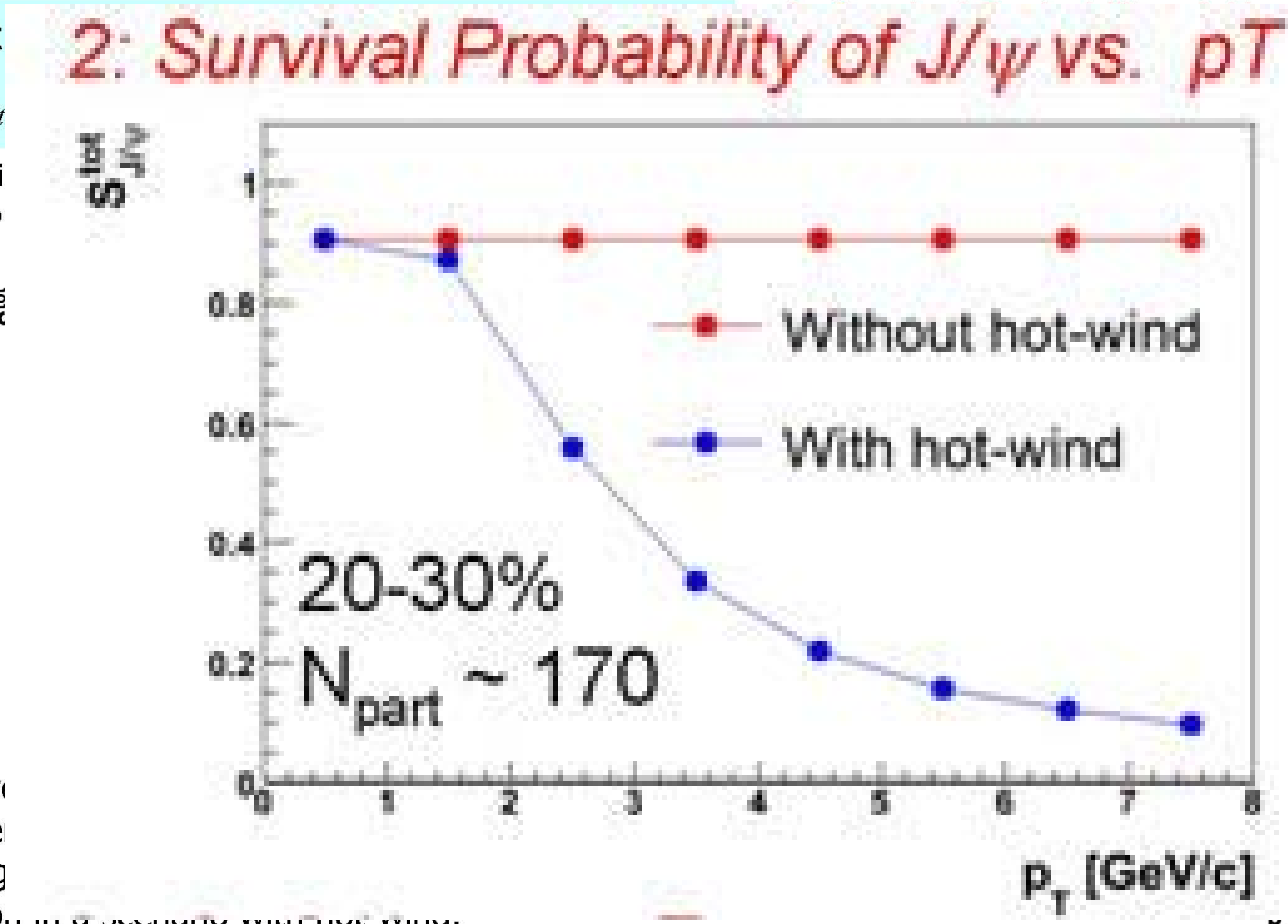
This effect may be tested at RHIC II or LHC

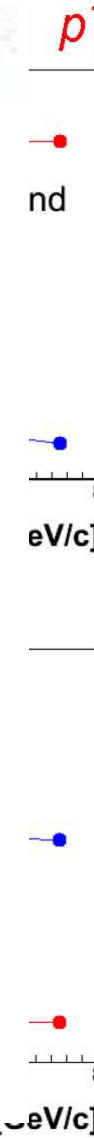
Hot-wind scenario in hydro+J/ψ model

T. Gunji, H. Hamagaki, T. Hatsuda, T. Hirano, Y. Akamatsu : Phys. Rev. C 76:051901 (R), 2007
Parallel talk at QM2008 by T. Gunji , Feb. 9th SessionXVIII 15:20~15:40

Melt
T_{melt}

Melti
10%





•J/ψ
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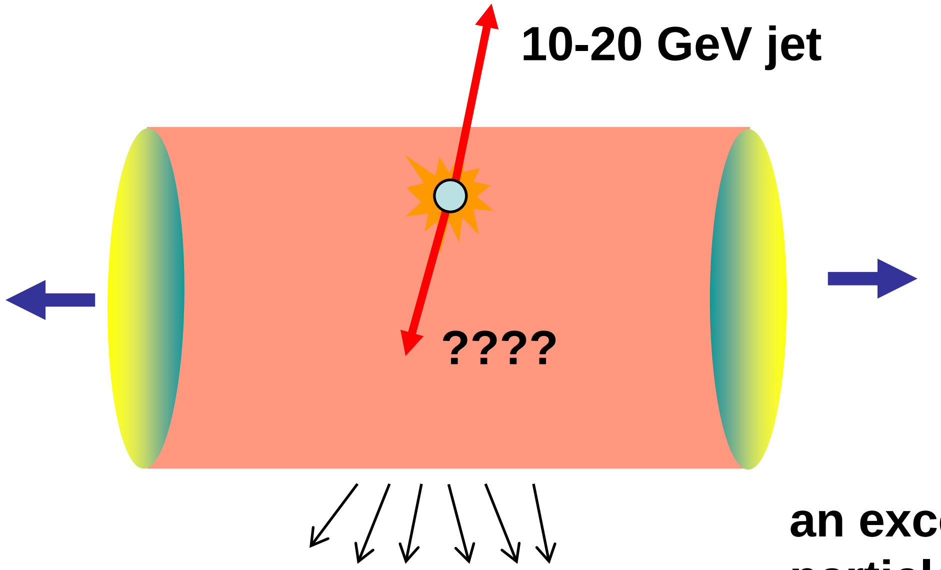
Jet Quenching



High energy partons lose energy quickly in the QGP

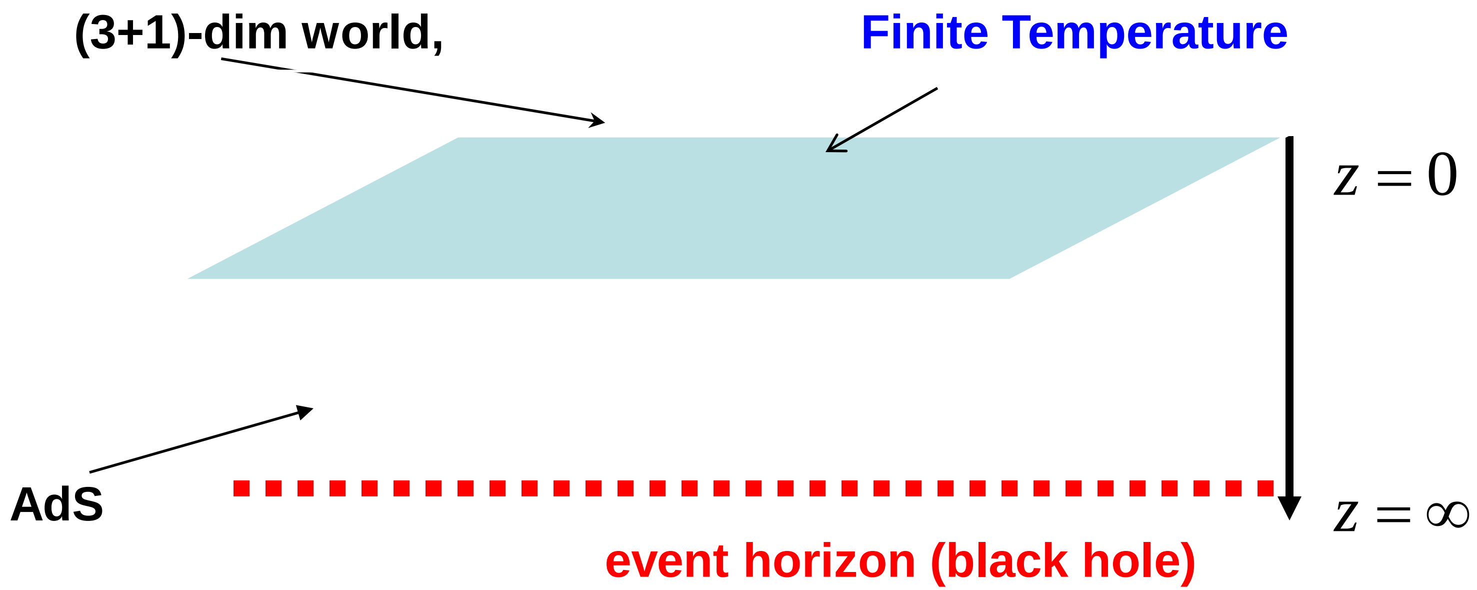
an excess of low energy particles redistributed to rather large angles

The presence of hot matter modifies the properties of jets.

Good probes of the QGP

Jet quenching from AdS/CFT: two approaches

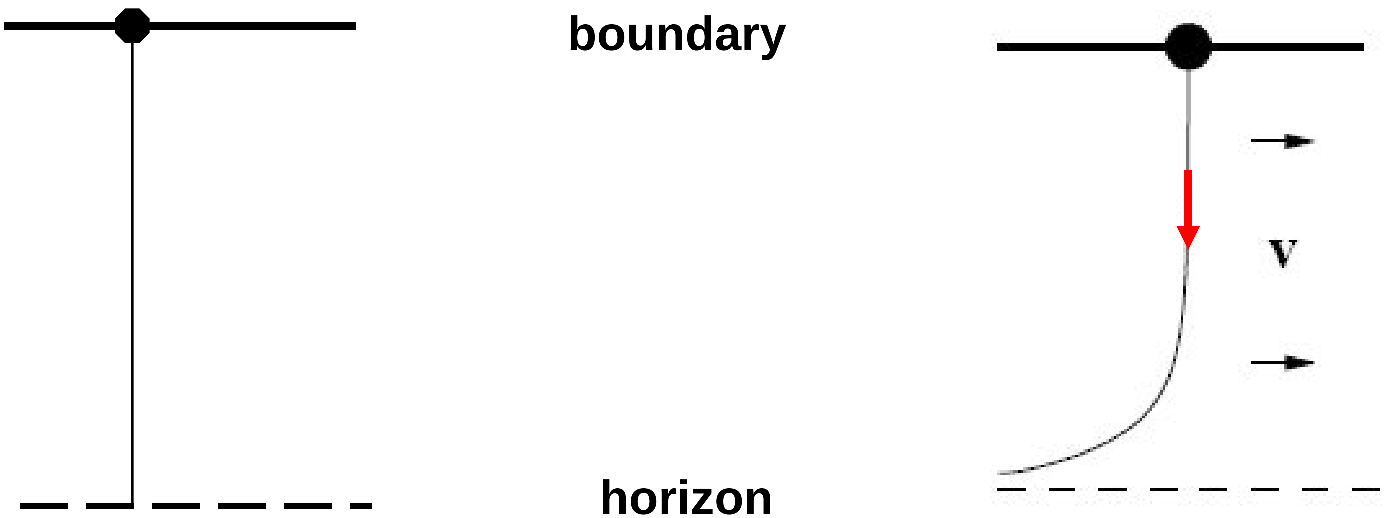
AdS/CFT



Our (3+1)-dimensional world lies at the boundary of AdS.

A moving quark in $\mathcal{N}$=4 QGP

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



Static quark in QGP

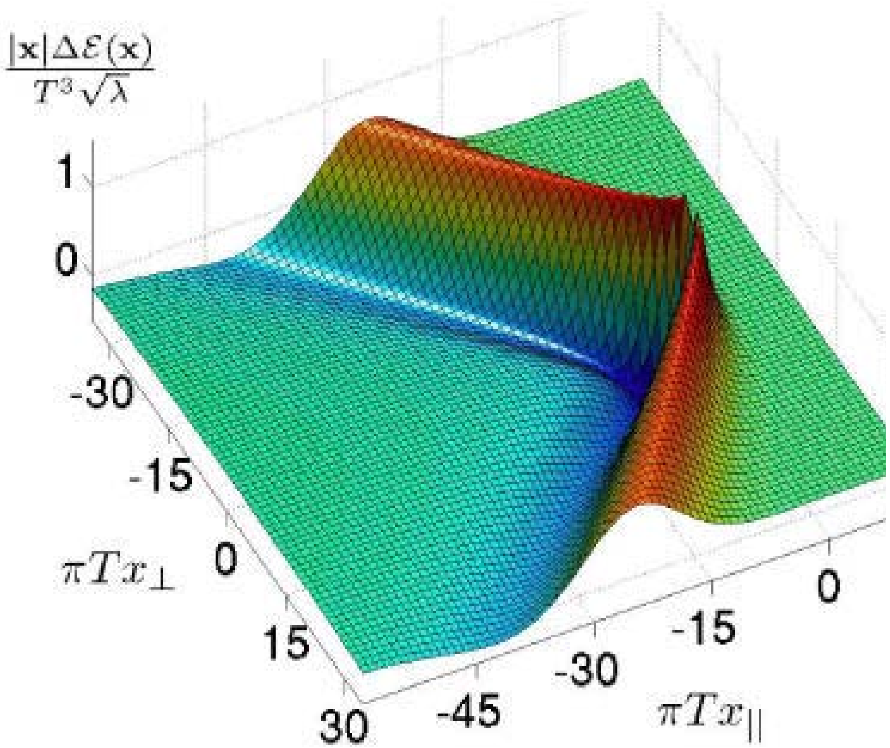
moving quark in QGP

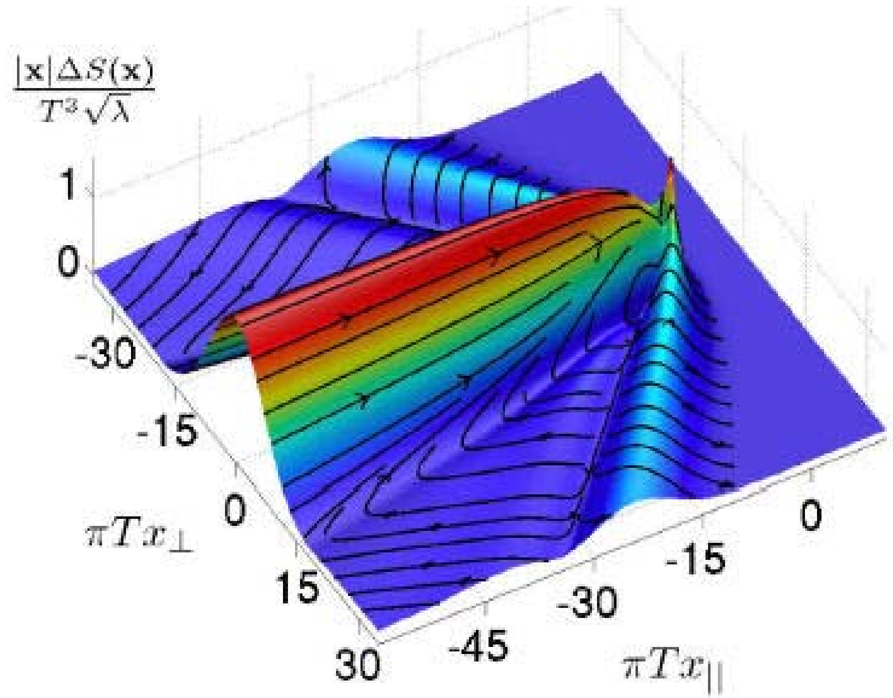
Drag: momentum flow down the string from quark to horizon.

$$\frac{dp}{dt} = -\mu p, \qquad \mu = \frac{\pi\sqrt{\lambda}}{2m}T^2$$ (independent of p)

Medium responses

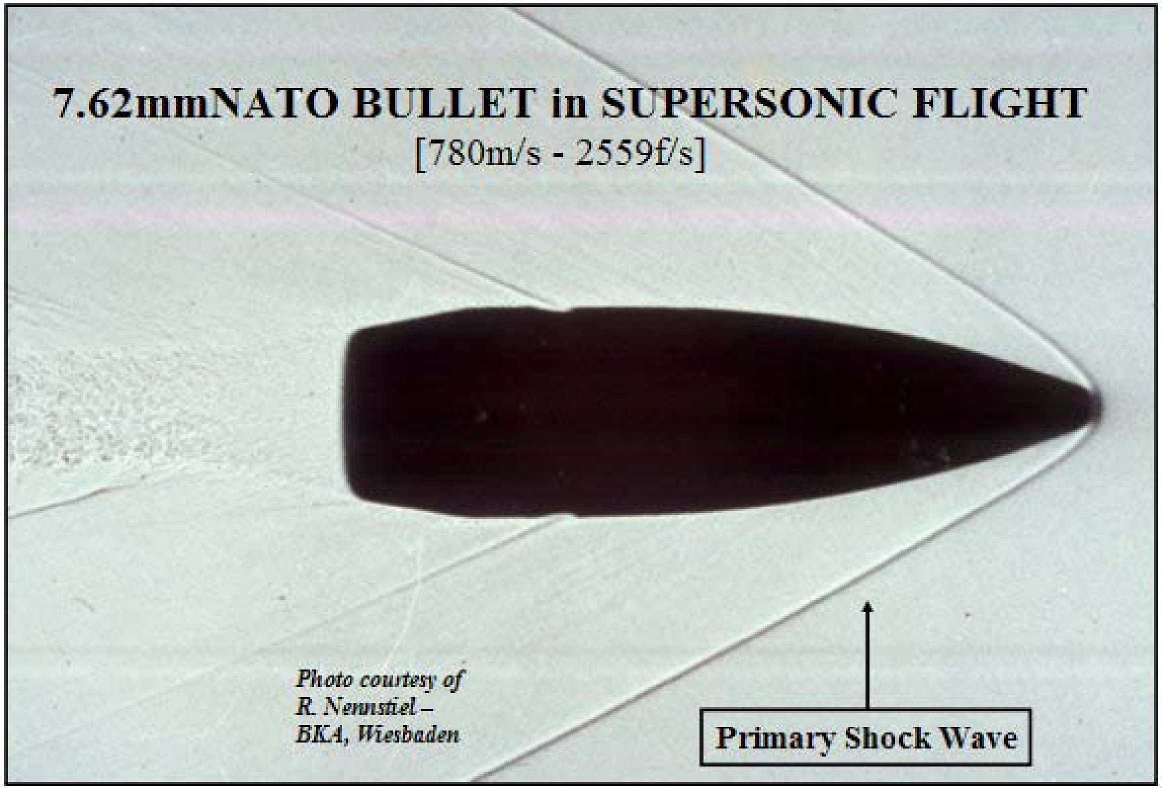
Medium response: $\left\langle T_{\mu\nu} \right\rangle$ **(due to the presence of the moving quark)**





Supersonic motion

Chesler , Yaffe, 0712.0050 See also Gubser, Pufu and Yarom


7.62mmNATO BULLET in SUPERSONIC FLIGHT
[780m/s - 2559f/s]
Photo courtesy of
R. Nennstiel –
BKA, Wiesbaden
Primary Shock Wave

Regime of validity: $m \gg \sqrt{\lambda}T$,

$$\gamma < \left(\frac{2m}{\sqrt{\lambda}T}\right)^2$$

Apply to heavy quarks, strongly coupled at all scales

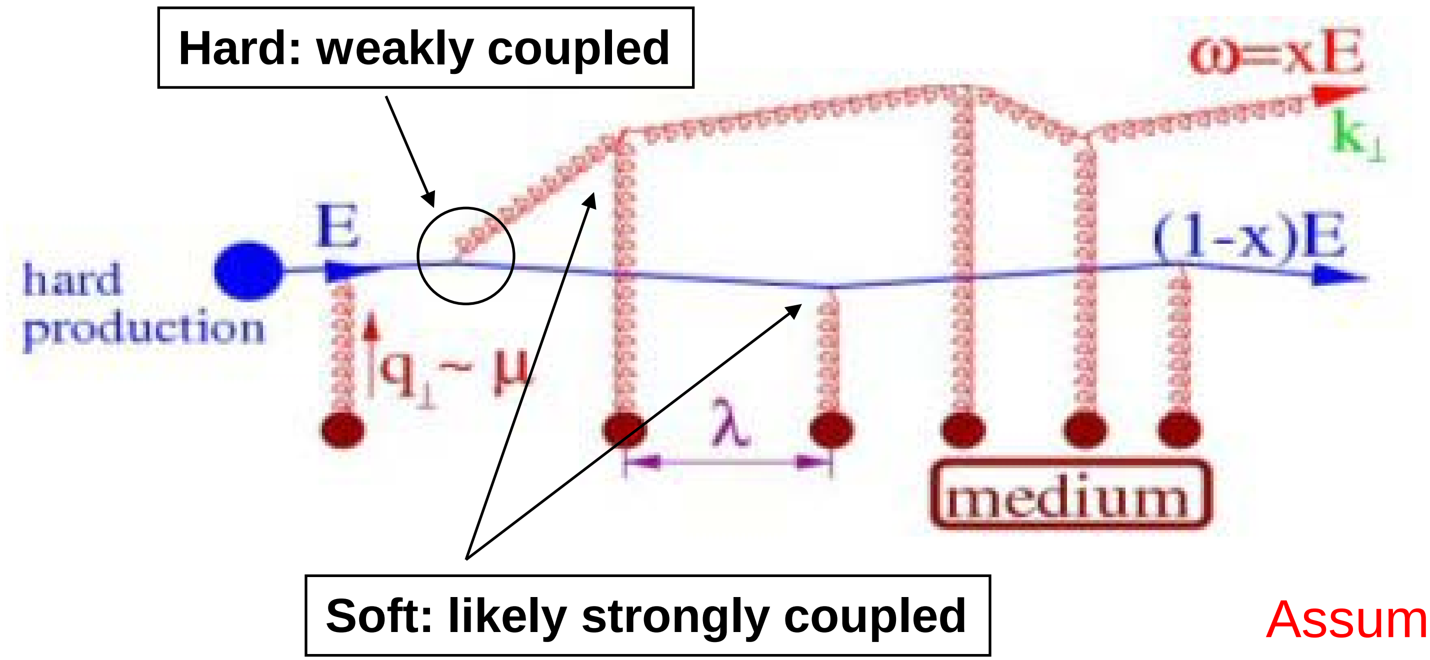
Jet quenching from Wilson Loop (I)

Basic idea:

- Due to asymptotic freedom, quark energy loss in the QGP of QCD can be separated into hard (weakly coupled) and soft (strongly coupled) parts.

- Use AdS/CFT to calculate the soft part.

Jet quenching from Wilson Loop (II)



Assume:
$E >> \omega >> k_\perp >> T$

The dominant effect of the medium on a high energy parton is medium-induced Bremsstrahlung.

$\hat{q}$: multiple rescatterings of hard partons with the medium

Jet quenching from Wilson Loop (III)

Zakharov, Wiedemann
HL, Rajagopal, Wiedemann

Soft scatterings are captured by Light like Wilson lines.

$\hat{q}$: can be evaluated non-perturbatively from thermal expectation value of a Light-like Wilson loop.

Calculate the light-like Wilson loop in AdS/CFT

From $\mathcal{N}$=4 SYM:

$$\hat{q}_{SYM} = \frac{\pi^{3/2}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3 \approx 26.69\sqrt{\alpha_{SYM}N_c}T^3$$

Jet Quenching parameter $\hat{q}$

Experimental estimate:

$\hat{q}$: 5-15 GeV^2/fm

Perturbation theory:

$\hat{q}$: < 1 GeV^2/fm

From $\mathcal{N}$=4 SYM: HL, Rajagopal, Wiedemann

$$\hat{q}_{SYM} = \frac{\pi^{3/2}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3 \approx 26.69\sqrt{\alpha_{SYM}N_c}T^3$$

$\hat{q}$ is NOT proportional to the number of scattering centers.

$$N_C = 3, \alpha_s = \frac{1}{2}, T = 300\ MeV \quad \hat{q}_{SYM} = 4.5\,\mathrm{GeV}^2/\mathrm{fm}.$$

Heavy ion collisions and AdS/CFT

String theory techniques provide qualitative, and semi-quantitative insights and predictions regarding properties of strongly interacting quark-gluon plasma.

Many other studies …….

String theory has immediate testable predictions for experiments after all

…….

Thank You !