Strongly coupled plasma - hydrodynamics, thermalization and nonequilibrium behavior

Romuald A. Janik

Jagiellonian University
Kraków

work with M. Heller, P. Witaszczyk
see RJ 1311.3966 [hep-ph] for a recent review

Outline

Why use AdS/CFT?

$\mathcal{N} = 4$ **plasma versus QCD plasma**

The AdS/CFT description of a plasma system

Boost-invariant flow

The transition to hydrodynamics and its characteristics

Nonequillibrium degrees of freedom

Conclusions

The AdS/CFT correspondence

$\boxed{\mathcal{N} = 4 \text{ Super Yang-Mills theory}}$	$\equiv$	$\boxed{\text{Superstrings on } AdS_5 \times S^5}$
strong coupling		(semi-)classical strings
nonperturbative physics		or supergravity
very difficult		'easy'
weak coupling		highly quantum regime
'easy'		very difficult

- New ways of looking at nonperturbative gauge theory physics...
- Intricate links with General Relativity...
- Has been extended to many other cases

The AdS/CFT correspondence

$\boxed{\mathcal{N} = 4 \text{ Super Yang-Mills theory}} \quad \equiv \quad \boxed{\text{Superstrings on } AdS_5 \times S^5}$

strong coupling	(semi-)classical strings
nonperturbative physics	or supergravity
very difficult	'easy'
weak coupling	highly quantum regime
'easy'	very difficult

- New ways of looking at nonperturbative gauge theory physics...
- Intricate links with General Relativity...
- Has been extended to many other cases

The AdS/CFT correspondence

$\boxed{\mathcal{N} = 4 \text{ Super Yang-Mills theory}} \quad \equiv \quad \boxed{\text{Superstrings on } AdS_5 \times S^5}$

strong coupling	(semi-)classical strings
nonperturbative physics	or supergravity
very difficult	'easy'
weak coupling	highly quantum regime
'easy'	very difficult

- New ways of looking at nonperturbative gauge theory physics...
- Intricate links with General Relativity...
- Has been extended to many other cases

The AdS/CFT correspondence

$\boxed{\mathcal{N} = 4 \text{ Super Yang-Mills theory}}$	$\equiv$	$\boxed{\text{Superstrings on } AdS_5 \times S^5}$
strong coupling		(semi-)classical strings
nonperturbative physics		or supergravity
very difficult		'easy'
weak coupling		highly quantum regime
'easy'		very difficult

- New ways of looking at nonperturbative gauge theory physics...
- Intricate links with General Relativity...
- Has been extended to many other cases

Why use AdS/CFT for quark-gluon plasma physics?

Problem:

- QCD plasma produced at RHIC/LHC is most probably a strongly coupled system
- Nonperturbative methods applicable to real time dynamics are very scarce
- Conventional lattice QCD is inherently Euclidean

AdS/CFT works equally well for Minkowski and Euclidean signature
– study similar problems in $\mathcal{N}=4$ SYM
– generalize later to other theories

Why use AdS/CFT for quark-gluon plasma physics?

Problem:

- QCD plasma produced at RHIC/LHC is most probably a strongly coupled system
- Nonperturbative methods applicable to real time dynamics are very scarce
- Conventional lattice QCD is inherently Euclidean

AdS/CFT works equally well for Minkowski and Euclidean signature
– study similar problems in $\mathcal{N}=4$ SYM
– generalize later to other theories

Why use AdS/CFT for quark-gluon plasma physics?

Problem:

- QCD plasma produced at RHIC/LHC is most probably a strongly coupled system
- Nonperturbative methods applicable to real time dynamics are very scarce
- Conventional lattice QCD is inherently Euclidean

AdS/CFT works equally well for Minkowski and Euclidean signature
– study similar problems in $\mathcal{N}=4$ SYM
– generalize later to other theories

Why use AdS/CFT for quark-gluon plasma physics?

Problem:

- QCD plasma produced at RHIC/LHC is most probably a strongly coupled system
- Nonperturbative methods applicable to real time dynamics are very scarce
- Conventional lattice QCD is inherently Euclidean

AdS/CFT works equally well for Minkowski and Euclidean signature
– study similar problems in $\mathcal{N}=4$ SYM
– generalize later to other theories

Why use AdS/CFT for quark-gluon plasma physics?

Problem:

- QCD plasma produced at RHIC/LHC is most probably a strongly coupled system
- Nonperturbative methods applicable to real time dynamics are very scarce
- Conventional lattice QCD is inherently Euclidean

AdS/CFT works equally well for Minkowski and Euclidean signature
– study similar problems in $\mathcal{N}=4$ SYM
– generalize later to other theories

Why use AdS/CFT for quark-gluon plasma physics?

Problem:

- QCD plasma produced at RHIC/LHC is most probably a strongly coupled system
- Nonperturbative methods applicable to real time dynamics are very scarce
- Conventional lattice QCD is inherently Euclidean

AdS/CFT works equally well for Minkowski and Euclidean signature
– study similar problems in $\mathcal{N}=4$ SYM
– generalize later to other theories

Why use AdS/CFT for quark-gluon plasma physics?

Problem:

- QCD plasma produced at RHIC/LHC is most probably a strongly coupled system
- Nonperturbative methods applicable to real time dynamics are very scarce
- Conventional lattice QCD is inherently Euclidean

AdS/CFT works equally well for Minkowski and Euclidean signature
– study similar problems in $\mathcal{N}=4$ SYM
– generalize later to other theories

Why use AdS/CFT for quark-gluon plasma physics?

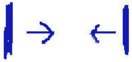
Problem:

- QCD plasma produced at RHIC/LHC is most probably a strongly coupled system
- Nonperturbative methods applicable to real time dynamics are very scarce
- Conventional lattice QCD is inherently Euclidean

AdS/CFT works equally well for Minkowski and Euclidean signature
– study similar problems in $\mathcal{N}=4$ SYM
– generalize later to other theories

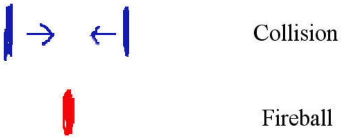
Point of reference: heavy-ion collision at RHIC/LHC:

Point of reference: heavy-ion collision at RHIC/LHC:

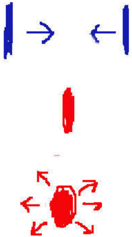


Collision

Point of reference: heavy-ion collision at RHIC/LHC:



Point of reference: heavy-ion collision at RHIC/LHC:

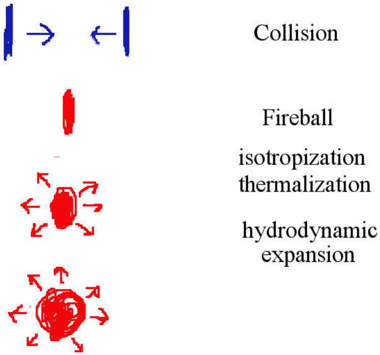


Collision

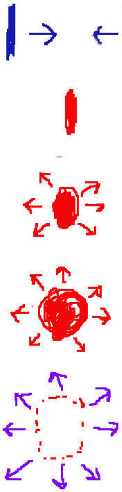
Fireball

isotropization
thermalization

Point of reference: heavy-ion collision at RHIC/LHC:



Point of reference: heavy-ion collision at RHIC/LHC:



Collision

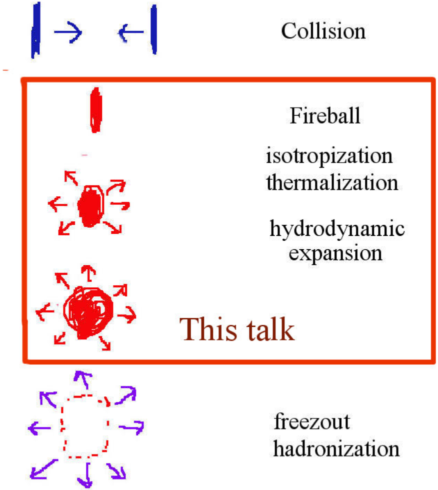
Fireball

isotropization
thermalization

hydrodynamic
expansion

freezout
hadronization

Point of reference: heavy-ion collision at RHIC/LHC:



$\mathcal{N} = 4$ plasma versus QCD plasma

Similarities:

- Deconfined phase
- Strongly coupled
- No supersymmetry!

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
- (Exactly) conformal equation of state $\longrightarrow$ Perhaps not so bad around $T \sim 1.5 - 2.5\, T_c$
- No confinement/deconfinement phase transition $\longrightarrow$ The $\mathcal{N} = 4$ plasma expands and cools indefinitely

One can pass to more complicated AdS/CFT setups and lift the above differences

$\mathcal{N}=4$ plasma versus QCD plasma

Similarities:

- Deconfined phase
- Strongly coupled
- No supersymmetry!

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
- (Exactly) conformal equation of state $\longrightarrow$ Perhaps not so bad around $T \sim 1.5 - 2.5\, T_c$
- No confinement/deconfinement phase transition $\longrightarrow$ The $\mathcal{N}=4$ plasma expands and cools indefinitely

One can pass to more complicated AdS/CFT setups and lift the above differences

$\mathcal{N} = 4$ plasma versus QCD plasma

Similarities:

- Deconfined phase
- Strongly coupled
- No supersymmetry!

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
- (Exactly) conformal equation of state $\longrightarrow$ Perhaps not so bad around $T \sim 1.5 - 2.5\,T_c$
- No confinement/deconfinement phase transition $\longrightarrow$ The $\mathcal{N} = 4$ plasma expands and cools indefinitely

One can pass to more complicated AdS/CFT setups and lift the above differences

$\mathcal{N} = 4$ plasma versus QCD plasma

Similarities:

- Deconfined phase
- Strongly coupled
- No supersymmetry!

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
- (Exactly) conformal equation of state $\longrightarrow$ Perhaps not so bad around $T \sim 1.5 - 2.5 T_c$
- No confinement/deconfinement phase transition $\longrightarrow$ The $\mathcal{N} = 4$ plasma expands and cools indefinitely

One can pass to more complicated AdS/CFT setups and lift the above differences

$\mathcal{N} = 4$ plasma versus QCD plasma

Similarities:

- Deconfined phase
- Strongly coupled
- No supersymmetry!

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
- (Exactly) conformal equation of state $\longrightarrow$ Perhaps not so bad around $T \sim 1.5 - 2.5 T_c$
- No confinement/deconfinement phase transition $\longrightarrow$ The $\mathcal{N} = 4$ plasma expands and cools indefinitely

One can pass to more complicated AdS/CFT setups and lift the above differences

$\mathcal{N} = 4$ plasma versus QCD plasma

Similarities:

- Deconfined phase
- Strongly coupled
- No supersymmetry!

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
- (Exactly) conformal equation of state $\longrightarrow$ Perhaps not so bad around $T \sim 1.5 - 2.5\, T_c$
- No confinement/deconfinement phase transition $\longrightarrow$ The $\mathcal{N} = 4$ plasma expands and cools indefinitely

One can pass to more complicated AdS/CFT setups and lift the above differences

$\mathcal{N} = 4$ plasma versus QCD plasma

Similarities:

- Deconfined phase
- Strongly coupled
- No supersymmetry!

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
- (Exactly) conformal equation of state $\longrightarrow$ Perhaps not so bad around $T \sim 1.5 - 2.5\,T_c$
- No confinement/deconfinement phase transition $\longrightarrow$ The $\mathcal{N} = 4$ plasma expands and cools indefinitely

One can pass to more complicated AdS/CFT setups and lift the above differences

$\mathcal{N} = 4$ plasma versus QCD plasma

Similarities:

- Deconfined phase
- Strongly coupled
- No supersymmetry!

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
- (Exactly) conformal equation of state $\longrightarrow$ Perhaps not so bad around $T \sim 1.5 - 2.5 T_c$
- No confinement/deconfinement phase transition $\longrightarrow$ The $\mathcal{N} = 4$ plasma expands and cools indefinitely

One can pass to more complicated AdS/CFT setups and lift the above differences

$\mathcal{N} = 4$ plasma versus QCD plasma

Similarities:

- Deconfined phase
- Strongly coupled
- No supersymmetry!

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
- (Exactly) conformal equation of state $\longrightarrow$ Perhaps not so bad around $T \sim 1.5 - 2.5\, T_c$
- No confinement/deconfinement phase transition $\longrightarrow$ The $\mathcal{N} = 4$ plasma expands and cools indefinitely

One can pass to more complicated AdS/CFT setups and lift the above differences

$\mathcal{N} = 4$ plasma versus QCD plasma

Similarities:

- Deconfined phase
- Strongly coupled
- No supersymmetry!

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
- (Exactly) conformal equation of state $\longrightarrow$ Perhaps not so bad around $T \sim 1.5 - 2.5\, T_c$
- No confinement/deconfinement phase transition $\longrightarrow$ The $\mathcal{N} = 4$ plasma expands and cools indefinitely

One can pass to more complicated AdS/CFT setups and lift the above differences

$\mathcal{N} = 4$ plasma versus QCD plasma

Similarities:

- Deconfined phase
- Strongly coupled
- No supersymmetry!

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
- (Exactly) conformal equation of state $\longrightarrow$ Perhaps not so bad around $T \sim 1.5 - 2.5\, T_c$
- No confinement/deconfinement phase transition $\longrightarrow$ The $\mathcal{N} = 4$ plasma expands and cools indefinitely

One can pass to more complicated AdS/CFT setups and lift the above differences

$\mathcal{N} = 4$ plasma versus QCD plasma

Similarities:

- Deconfined phase
- Strongly coupled
- No supersymmetry!

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
- (Exactly) conformal equation of state $\longrightarrow$ Perhaps not so bad around $T \sim 1.5 - 2.5\, T_c$
- No confinement/deconfinement phase transition $\longrightarrow$ The $\mathcal{N} = 4$ plasma expands and cools indefinitely

One can pass to more complicated AdS/CFT setups and lift the above differences

Why study $\mathcal{N} = 4$ plasma?

- The applicability of using $\mathcal{N} = 4$ plasma to model real world phenomenae dependes on the questions asked..
- Use it as a theoretical laboratory where we may compute from 'first principles' nonequilibrium nonperturbative dynamics
- Gain qualitative insight into the physics which is very difficult to access using other methods
- Discover some universal properties? (like η/s)

- For $\mathcal{N} = 4$ plasma the AdS/CFT correspondence is technically simplest
- Use the results on strong coupling properties of $\mathcal{N} = 4$ plasma as a point of reference for analyzing/describing QCD plasma
- Eventually one may consider more realistic theories with AdS/CFT duals...

Why study $\mathcal{N} = 4$ plasma?

- The applicability of using $\mathcal{N} = 4$ plasma to model real world phenomenae dependes on the questions asked..
- Use it as a theoretical laboratory where we may compute from 'first principles' nonequilibrium nonperturbative dynamics
- Gain qualitative insight into the physics which is very difficult to access using other methods
- Discover some universal properties? (like η/s)

- For $\mathcal{N} = 4$ plasma the AdS/CFT correspondence is technically simplest
- Use the results on strong coupling properties of $\mathcal{N} = 4$ plasma as a point of reference for analyzing/describing QCD plasma
- Eventually one may consider more realistic theories with AdS/CFT duals...

Why study $\mathcal{N} = 4$ plasma?

- The applicability of using $\mathcal{N} = 4$ plasma to model real world phenomenae dependes on the questions asked..
- Use it as a theoretical laboratory where we may compute from 'first principles' nonequilibrium nonperturbative dynamics
- Gain qualitative insight into the physics which is very difficult to access using other methods
- Discover some universal properties? (like η/s)

- For $\mathcal{N} = 4$ plasma the AdS/CFT correspondence is technically simplest
- Use the results on strong coupling properties of $\mathcal{N} = 4$ plasma as a point of reference for analyzing/describing QCD plasma
- Eventually one may consider more realistic theories with AdS/CFT duals...

Why study $\mathcal{N} = 4$ plasma?

- The applicability of using $\mathcal{N} = 4$ plasma to model real world phenomenae dependes on the questions asked..
- Use it as a theoretical laboratory where we may compute from 'first principles' nonequilibrium nonperturbative dynamics
- Gain qualitative insight into the physics which is very difficult to access using other methods
- Discover some universal properties? (like η/s)

- For $\mathcal{N} = 4$ plasma the AdS/CFT correspondence is technically simplest
- Use the results on strong coupling properties of $\mathcal{N} = 4$ plasma as a point of reference for analyzing/describing QCD plasma
- Eventually one may consider more realistic theories with AdS/CFT duals...

Why study $\mathcal{N} = 4$ plasma?

- The applicability of using $\mathcal{N} = 4$ plasma to model real world phenomenae dependes on the questions asked..
- Use it as a theoretical laboratory where we may compute from 'first principles' nonequilibrium nonperturbative dynamics
- Gain qualitative insight into the physics which is very difficult to access using other methods
- Discover some universal properties? (like η/s)

- For $\mathcal{N} = 4$ plasma the AdS/CFT correspondence is technically simplest
- Use the results on strong coupling properties of $\mathcal{N} = 4$ plasma as a point of reference for analyzing/describing QCD plasma
- Eventually one may consider more realistic theories with AdS/CFT duals...

Why study $\mathcal{N} = 4$ plasma?

- The applicability of using $\mathcal{N} = 4$ plasma to model real world phenomenae dependes on the questions asked..
- Use it as a theoretical laboratory where we may compute from 'first principles' nonequilibrium nonperturbative dynamics
- Gain qualitative insight into the physics which is very difficult to access using other methods
- Discover some universal properties? (like η/s)

- For $\mathcal{N} = 4$ plasma the AdS/CFT correspondence is technically simplest
- Use the results on strong coupling properties of $\mathcal{N} = 4$ plasma as a point of reference for analyzing/describing QCD plasma
- Eventually one may consider more realistic theories with AdS/CFT duals...

Why study $\mathcal{N} = 4$ plasma?

- The applicability of using $\mathcal{N} = 4$ plasma to model real world phenomenae dependes on the questions asked..
- Use it as a theoretical laboratory where we may compute from 'first principles' nonequilibrium nonperturbative dynamics
- Gain qualitative insight into the physics which is very difficult to access using other methods
- Discover some universal properties? (like η/s)

- For $\mathcal{N} = 4$ plasma the AdS/CFT correspondence is technically simplest
- Use the results on strong coupling properties of $\mathcal{N} = 4$ plasma as a point of reference for analyzing/describing QCD plasma
- Eventually one may consider more realistic theories with AdS/CFT duals...

The AdS/CFT description

Aim: Describe the time dependent evolving strongly coupled plasma system

$\downarrow$

Describe it in terms of lightest degrees of freedom on the AdS side which are relevant at strong coupling

$\downarrow$

$$ds^2 = \frac{g_{\mu\nu}(x^\rho, z) dx^\mu dx^\nu + dz^2}{z^2} \equiv g^{5D}_{\alpha\beta} dx^\alpha dx^\beta$$

$\downarrow$

Compute the time-evolution by solving (numerically) 5D Einstein's equations

$$R_{\alpha\beta} - \frac{1}{2} g^{5D}_{\alpha\beta} R - 6\, g^{5D}_{\alpha\beta} = 0$$

$\downarrow$

Extract physical observables (like $\langle T^{\mu\nu}(x^\rho) \rangle$) from the numerical geometry

The AdS/CFT description

Aim: Describe the time dependent evolving strongly coupled plasma system

$\downarrow$

Describe it in terms of lightest degrees of freedom on the AdS side which are relevant at strong coupling

$\downarrow$

$$ds^2 = \frac{g_{\mu\nu}(x^\rho, z) dx^\mu dx^\nu + dz^2}{z^2} \equiv g^{5D}_{\alpha\beta} dx^\alpha dx^\beta$$

$\downarrow$

Compute the time-evolution by solving (numerically) 5D Einstein's equations

$$R_{\alpha\beta} - \frac{1}{2} g^{5D}_{\alpha\beta} R - 6\, g^{5D}_{\alpha\beta} = 0$$

$\downarrow$

Extract physical observables (like $\langle T^{\mu\nu}(x^\rho) \rangle$) from the numerical geometry

The AdS/CFT description

Aim: Describe the time dependent evolving strongly coupled plasma system

$\downarrow$

Describe it in terms of lightest degrees of freedom on the AdS side which are relevant at strong coupling

$\downarrow$

$$ds^2 = \frac{g_{\mu\nu}(x^\rho, z) dx^\mu dx^\nu + dz^2}{z^2} \equiv g^{5D}_{\alpha\beta} dx^\alpha dx^\beta$$

$\downarrow$

Compute the time-evolution by solving (numerically) 5D Einstein's equations

$$R_{\alpha\beta} - \frac{1}{2} g^{5D}_{\alpha\beta} R - 6\, g^{5D}_{\alpha\beta} = 0$$

$\downarrow$

Extract physical observables (like $\langle T^{\mu\nu}(x^\rho)\rangle$) from the numerical geometry

The AdS/CFT description

Aim: Describe the time dependent evolving strongly coupled plasma system

$\downarrow$

Describe it in terms of lightest degrees of freedom on the AdS side which are relevant at strong coupling

$\downarrow$

$$ds^2 = \frac{g_{\mu\nu}(x^\rho, z)dx^\mu dx^\nu + dz^2}{z^2} \equiv g^{5D}_{\alpha\beta} dx^\alpha dx^\beta$$

$\downarrow$

Compute the time-evolution by solving (numerically) 5D Einstein's equations

$$R_{\alpha\beta} - \frac{1}{2} g^{5D}_{\alpha\beta} R - 6\, g^{5D}_{\alpha\beta} = 0$$

$\downarrow$

Extract physical observables (like $\langle T^{\mu\nu}(x^\rho) \rangle$) from the numerical geometry

The AdS/CFT description

Aim: Describe the time dependent evolving strongly coupled plasma system

$\downarrow$

Describe it in terms of lightest degrees of freedom on the AdS side which are relevant at strong coupling

$\downarrow$

$$ds^2 = \frac{g_{\mu\nu}(x^\rho, z)dx^\mu dx^\nu + dz^2}{z^2} \equiv g^{5D}_{\alpha\beta} dx^\alpha dx^\beta$$

$\downarrow$

Compute the time-evolution by solving (numerically) 5D Einstein's equations

$$R_{\alpha\beta} - \frac{1}{2} g^{5D}_{\alpha\beta} R - 6\, g^{5D}_{\alpha\beta} = 0$$

$\downarrow$

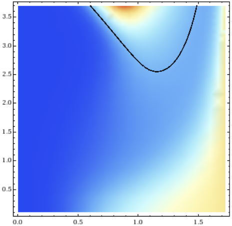
Extract physical observables (like $\langle T^{\mu\nu}(x^\rho)\rangle$) from the numerical geometry

What physics can we extract?

- Asymptotics of $g_{\mu\nu}(x^\rho, z)$ at $z \sim 0$ gives the energy-momentum tensor $T_{\mu\nu}(x^\rho)$ of the plasma system
- We can test whether $T_{\mu\nu}(x^\rho)$ is of a hydrodynamic form...
- We can check for local thermal equilibrium

- The area of the apparent horizon defines for us the entropy density
- We observe some *initial entropy*

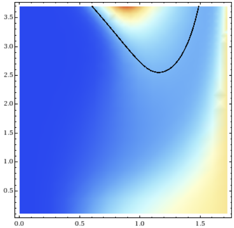
What physics can we extract?



- Asymptotics of $g_{\mu\nu}(x^\rho, z)$ at $z \sim 0$ gives the energy-momentum tensor $T_{\mu\nu}(x^\rho)$ of the plasma system
- We can test whether $T_{\mu\nu}(x^\rho)$ is of a hydrodynamic form...
- We can check for local thermal equilibrium

- The area of the apparent horizon defines for us the entropy density
- We observe some *initial entropy*

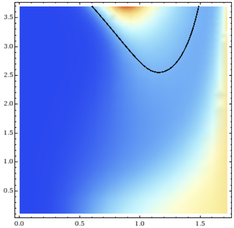
What physics can we extract?



- Asymptotics of $g_{\mu\nu}(x^\rho, z)$ at $z \sim 0$ gives the energy-momentum tensor $T_{\mu\nu}(x^\rho)$ of the plasma system
- We can test whether $T_{\mu\nu}(x^\rho)$ is of a hydrodynamic form...
- We can check for local thermal equilibrium

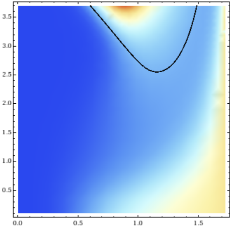
- The area of the apparent horizon defines for us the entropy density
- We observe some *initial entropy*

What physics can we extract?



- Asymptotics of $g_{\mu\nu}(x^\rho, z)$ at $z \sim 0$ gives the energy-momentum tensor $T_{\mu\nu}(x^\rho)$ of the plasma system
- We can test whether $T_{\mu\nu}(x^\rho)$ is of a hydrodynamic form...
- We can check for local thermal equilibrium
- The area of the apparent horizon defines for us the entropy density
- We observe some *initial entropy*

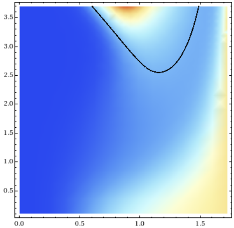
What physics can we extract?



- Asymptotics of $g_{\mu\nu}(x^\rho, z)$ at $z \sim 0$ gives the energy-momentum tensor $T_{\mu\nu}(x^\rho)$ of the plasma system
- We can test whether $T_{\mu\nu}(x^\rho)$ is of a hydrodynamic form...
- We can check for local thermal equilibrium

- The area of the apparent horizon defines for us the entropy density
- We observe some *initial entropy*

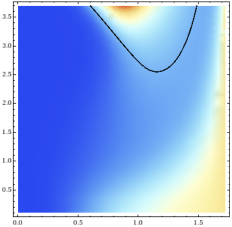
What physics can we extract?



- Asymptotics of $g_{\mu\nu}(x^\rho, z)$ at $z \sim 0$ gives the energy-momentum tensor $T_{\mu\nu}(x^\rho)$ of the plasma system
- We can test whether $T_{\mu\nu}(x^\rho)$ is of a hydrodynamic form...
- We can check for local thermal equilibrium

- The area of the apparent horizon defines for us the entropy density
- We observe some *initial entropy*

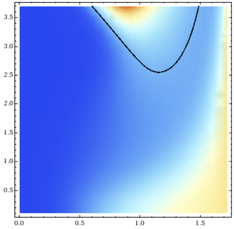
What physics can we extract?

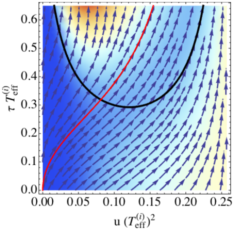


- Asymptotics of $g_{\mu\nu}(x^\rho, z)$ at $z \sim 0$ gives the energy-momentum tensor $T_{\mu\nu}(x^\rho)$ of the plasma system
- We can test whether $T_{\mu\nu}(x^\rho)$ is of a hydrodynamic form...
- We can check for local thermal equilibrium

- The area of the apparent horizon defines for us the entropy density
- We observe some *initial entropy*

What physics can we extract?

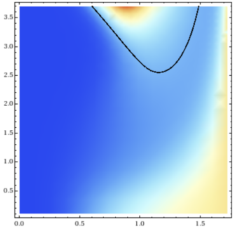


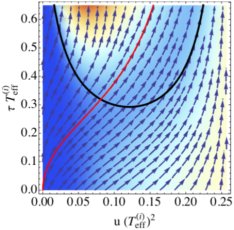


- Asymptotics of $g_{\mu\nu}(x^\rho, z)$ at $z \sim 0$ gives the energy-momentum tensor $T_{\mu\nu}(x^\rho)$ of the plasma system
- We can test whether $T_{\mu\nu}(x^\rho)$ is of a hydrodynamic form...
- We can check for local thermal equilibrium

- The area of the apparent horizon defines for us the entropy density
- We observe some *initial entropy*

What physics can we extract?





- Asymptotics of $g_{\mu\nu}(x^\rho, z)$ at $z \sim 0$ gives the energy-momentum tensor $T_{\mu\nu}(x^\rho)$ of the plasma system
- We can test whether $T_{\mu\nu}(x^\rho)$ is of a hydrodynamic form...
- We can check for local thermal equilibrium

- The area of the apparent horizon defines for us the entropy density
- We observe some *initial entropy*

Key question:

Understand the features of the far-from equilibrium stage of the dynamics of the strongly coupled plasma system

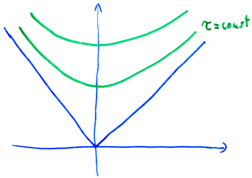
Key question:

Understand the features of the far-from equilibrium stage of the dynamics of the strongly coupled plasma system

Boost-invariant flow

Bjorken '83

Assume a flow that is invariant under longitudinal boosts and does not depend on the transverse coordinates.



- In a conformal theory, $T^\mu_\mu = 0$ and $\partial_\mu T^{\mu\nu} = 0$ determine, under the above assumptions, the energy-momentum tensor completely in terms of a single function $\varepsilon(\tau)$, the energy density at mid-rapidity.
- The longitudinal and transverse pressures are then given by

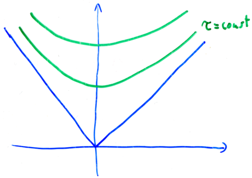
$$p_L = -\varepsilon - \tau \frac{d}{d\tau}\varepsilon \quad \text{and} \quad p_T = \varepsilon + \frac{1}{2}\tau \frac{d}{d\tau}\varepsilon \,.$$

- The assumptions of symmetry fix uniquely the flow velocity

Boost-invariant flow

Bjorken '83

Assume a flow that is invariant under longitudinal boosts and does not depend on the transverse coordinates.



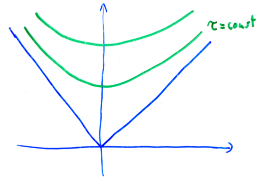
- In a conformal theory, $T^{\mu}_{\mu} = 0$ and $\partial_\mu T^{\mu\nu} = 0$ determine, under the above assumptions, the energy-momentum tensor completely in terms of a single function $\varepsilon(\tau)$, the energy density at mid-rapidity.
- The longitudinal and transverse pressures are then given by

$$p_L = -\varepsilon - \tau \frac{d}{d\tau}\varepsilon \quad \text{and} \quad p_T = \varepsilon + \frac{1}{2}\tau \frac{d}{d\tau}\varepsilon \,.$$

- The assumptions of symmetry fix uniquely the flow velocity

Boost-invariant flow

Bjorken '83
Assume a flow that is invariant under longitudinal boosts and does not depend on the transverse coordinates.



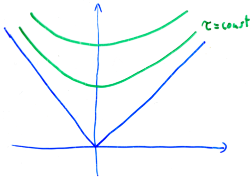
- In a conformal theory, $T_\mu^\mu = 0$ and $\partial_\mu T^{\mu\nu} = 0$ determine, under the above assumptions, the energy-momentum tensor completely in terms of a single function $\varepsilon(\tau)$, the energy density at mid-rapidity.
- The longitudinal and transverse pressures are then given by

$$p_L = -\varepsilon - \tau \frac{d}{d\tau}\varepsilon \quad \text{and} \quad p_T = \varepsilon + \frac{1}{2}\tau \frac{d}{d\tau}\varepsilon \,.$$

- The assumptions of symmetry fix uniquely the flow velocity

Boost-invariant flow

Bjorken '83
Assume a flow that is invariant under longitudinal boosts and does not depend on the transverse coordinates.



- In a conformal theory, $T^\mu_\mu = 0$ and $\partial_\mu T^{\mu\nu} = 0$ determine, under the above assumptions, the energy-momentum tensor completely in terms of a single function $\varepsilon(\tau)$, the energy density at mid-rapidity.
- The longitudinal and transverse pressures are then given by

$$p_L = -\varepsilon - \tau \frac{d}{d\tau}\varepsilon \quad \text{and} \quad p_T = \varepsilon + \frac{1}{2}\tau \frac{d}{d\tau}\varepsilon\,.$$

- The assumptions of symmetry fix uniquely the flow velocity

Large τ behaviour of $\varepsilon(\tau)$

- Structure of the analytical result for large τ:

$$\varepsilon(\tau) = \frac{1}{\tau^{\frac{4}{3}}} - \frac{2}{2^{\frac{1}{2}}3^{\frac{3}{4}}}\frac{1}{\tau^2} + \frac{1+2\log 2}{12\sqrt{3}}\frac{1}{\tau^{\frac{8}{3}}} + \frac{-3+2\pi^2+24\log 2-24\log^2 2}{324\cdot 2^{\frac{1}{2}}3^{\frac{1}{4}}}\frac{1}{\tau^{\frac{10}{3}}} + \ldots$$

RJ, Peschanski; Nakamura, S-J Sin; RJ; RJ, Heller; Heller

- Leading term — perfect fluid behaviour
  second term — 1^{st} order viscous hydrodynamics
  third term — 2^{nd} order viscous hydrodynamics
  fourth term — 3^{rd} order viscous hydrodynamics...
- In general:

$$\varepsilon(\tau) = \sum_{n=2}^{\infty} \frac{\varepsilon_n}{\tau^{\frac{2n}{3}}}$$

- Currently we know 240 terms in this expansion

Heller, RJ, Witaszczyk

- The hydrodynamic series is only asymptotic and has zero radius of convergence...

Heller, RJ, Witaszczyk 1302.0697 [PRL 110 (2013) 211602]

Large τ behaviour of $\varepsilon(\tau)$

- Structure of the analytical result for large τ:

$$\varepsilon(\tau) = \frac{1}{\tau^{\frac{4}{3}}} - \frac{2}{2^{\frac{1}{2}} 3^{\frac{3}{4}}} \frac{1}{\tau^2} + \frac{1 + 2\log 2}{12\sqrt{3}} \frac{1}{\tau^{\frac{8}{3}}} + \frac{-3 + 2\pi^2 + 24\log 2 - 24\log^2 2}{324 \cdot 2^{\frac{1}{2}} 3^{\frac{1}{4}}} \frac{1}{\tau^{\frac{10}{3}}} + \dots$$

RJ, Peschanski; Nakamura, S-J Sin; RJ; RJ, Heller; Heller

- Leading term — perfect fluid behaviour
  second term — 1^{st} order viscous hydrodynamics
  third term — 2^{nd} order viscous hydrodynamics
  fourth term — 3^{rd} order viscous hydrodynamics...
- In general:

$$\varepsilon(\tau) = \sum_{n=2}^{\infty} \frac{\varepsilon_n}{\tau^{\frac{2n}{3}}}$$

- Currently we know 240 terms in this expansion

Heller, RJ, Witaszczyk

- The hydrodynamic series is only asymptotic and has zero radius of convergence...

Heller, RJ, Witaszczyk 1302.0697 [PRL 110 (2013) 211602]

Large τ behaviour of $\varepsilon(\tau)$

- Structure of the analytical result for large τ:

$$\varepsilon(\tau) = \frac{1}{\tau^{\frac{4}{3}}} - \frac{2}{2^{\frac{1}{2}} 3^{\frac{3}{4}}} \frac{1}{\tau^2} + \frac{1 + 2\log 2}{12\sqrt{3}} \frac{1}{\tau^{\frac{8}{3}}} + \frac{-3 + 2\pi^2 + 24\log 2 - 24\log^2 2}{324 \cdot 2^{\frac{1}{2}} 3^{\frac{1}{4}}} \frac{1}{\tau^{\frac{10}{3}}} + \ldots$$

RJ, Peschanski; Nakamura, S-J Sin; RJ; RJ, Heller; Heller

- Leading term — perfect fluid behaviour
  second term — 1^{st} order viscous hydrodynamics
  third term — 2^{nd} order viscous hydrodynamics
  fourth term — 3^{rd} order viscous hydrodynamics...
- In general:

$$\varepsilon(\tau) = \sum_{n=2}^{\infty} \frac{\varepsilon_n}{\tau^{\frac{2n}{3}}}$$

- Currently we know 240 terms in this expansion

Heller, RJ, Witaszczyk

- The hydrodynamic series is only asymptotic and has zero radius of convergence...

Heller, RJ, Witaszczyk 1302.0697 [PRL 110 (2013) 211602]

Large τ behaviour of $\varepsilon(\tau)$

- Structure of the analytical result for large τ:

$$\varepsilon(\tau) = \frac{1}{\tau^{\frac{4}{3}}} - \frac{2}{2^{\frac{1}{2}} 3^{\frac{3}{4}}} \frac{1}{\tau^2} + \frac{1 + 2\log 2}{12\sqrt{3}} \frac{1}{\tau^{\frac{8}{3}}} + \frac{-3 + 2\pi^2 + 24\log 2 - 24\log^2 2}{324 \cdot 2^{\frac{1}{2}} 3^{\frac{1}{4}}} \frac{1}{\tau^{\frac{10}{3}}} + \ldots$$

RJ, Peschanski; Nakamura, S-J Sin; RJ; RJ, Heller; Heller

- Leading term — perfect fluid behaviour
  second term — 1^{st} order viscous hydrodynamics
  third term — 2^{nd} order viscous hydrodynamics
  fourth term — 3^{rd} order viscous hydrodynamics...

- In general:

$$\varepsilon(\tau) = \sum_{n=2}^{\infty} \frac{\varepsilon_n}{\tau^{\frac{2n}{3}}}$$

- Currently we know 240 terms in this expansion

Heller, RJ, Witaszczyk

- The hydrodynamic series is only asymptotic and has zero radius of convergence...

Heller, RJ, Witaszczyk 1302.0697 [PRL 110 (2013) 211602]

Large τ behaviour of $\varepsilon(\tau)$

- Structure of the analytical result for large τ:

$$\varepsilon(\tau) = \frac{1}{\tau^{\frac{4}{3}}} - \frac{2}{2^{\frac{1}{2}}3^{\frac{3}{4}}}\frac{1}{\tau^2} + \frac{1+2\log 2}{12\sqrt{3}}\frac{1}{\tau^{\frac{8}{3}}} + \frac{-3+2\pi^2+24\log 2-24\log^2 2}{324\cdot 2^{\frac{1}{2}}3^{\frac{1}{4}}}\frac{1}{\tau^{\frac{10}{3}}} + \ldots$$

RJ, Peschanski; Nakamura, S-J Sin; RJ; RJ, Heller; Heller

- Leading term — perfect fluid behaviour
second term — 1^{st} order viscous hydrodynamics
third term — 2^{nd} order viscous hydrodynamics
fourth term — 3^{rd} order viscous hydrodynamics...

- In general:

$$\varepsilon(\tau) = \sum_{n=2}^{\infty} \frac{\varepsilon_n}{\tau^{\frac{2n}{3}}}$$

- Currently we know 240 terms in this expansion

Heller, RJ, Witaszczyk

- The hydrodynamic series is only asymptotic and has zero radius of convergence...

Heller, RJ, Witaszczyk 1302.0697 [PRL 110 (2013) 211602]

Large τ behaviour of $\varepsilon(\tau)$

- Structure of the analytical result for large τ:

$$\varepsilon(\tau) = \frac{1}{\tau^{\frac{4}{3}}} - \frac{2}{2^{\frac{1}{2}}3^{\frac{3}{4}}}\frac{1}{\tau^2} + \frac{1+2\log 2}{12\sqrt{3}}\frac{1}{\tau^{\frac{8}{3}}} + \frac{-3+2\pi^2+24\log 2 - 24\log^2 2}{324\cdot 2^{\frac{1}{2}}3^{\frac{1}{4}}}\frac{1}{\tau^{\frac{10}{3}}} + \ldots$$

RJ, Peschanski; Nakamura, S-J Sin; RJ; RJ, Heller; Heller

- Leading term — perfect fluid behaviour
  second term — 1^{st} order viscous hydrodynamics
  third term — 2^{nd} order viscous hydrodynamics
  fourth term — 3^{rd} order viscous hydrodynamics...
- In general:

$$\varepsilon(\tau) = \sum_{n=2}^{\infty} \frac{\varepsilon_n}{\tau^{\frac{2n}{3}}}$$

- Currently we know 240 terms in this expansion

Heller, RJ, Witaszczyk

- The hydrodynamic series is only asymptotic and has zero radius of convergence...

Heller, RJ, Witaszczyk 1302.0697 [PRL 110 (2013) 211602]

Large τ behaviour of $\varepsilon(\tau)$

- Structure of the analytical result for large τ:

$$\varepsilon(\tau) = \frac{1}{\tau^{\frac{4}{3}}} - \frac{2}{2^{\frac{1}{2}}3^{\frac{3}{4}}}\frac{1}{\tau^2} + \frac{1+2\log 2}{12\sqrt{3}}\frac{1}{\tau^{\frac{8}{3}}} + \frac{-3+2\pi^2+24\log 2-24\log^2 2}{324\cdot 2^{\frac{1}{2}}3^{\frac{1}{4}}}\frac{1}{\tau^{\frac{10}{3}}} + \ldots$$

RJ, Peschanski; Nakamura, S-J Sin; RJ; RJ, Heller; Heller

- Leading term — perfect fluid behaviour
  second term — 1^{st} order viscous hydrodynamics
  third term — 2^{nd} order viscous hydrodynamics
  fourth term — 3^{rd} order viscous hydrodynamics...
- In general:

$$\varepsilon(\tau) = \sum_{n=2}^{\infty} \frac{\varepsilon_n}{\tau^{\frac{2n}{3}}}$$

- Currently we know 240 terms in this expansion

Heller, RJ, Witaszczyk

- The hydrodynamic series is only asymptotic and has zero radius of convergence...

Heller, RJ, Witaszczyk 1302.0697 [PRL 110 (2013) 211602]

Large τ behaviour of $\varepsilon(\tau)$

- Structure of the analytical result for large τ:

$$\varepsilon(\tau) = \frac{1}{\tau^{\frac{4}{3}}} - \frac{2}{2^{\frac{1}{2}} 3^{\frac{3}{4}}} \frac{1}{\tau^2} + \frac{1 + 2\log 2}{12\sqrt{3}} \frac{1}{\tau^{\frac{8}{3}}} + \frac{-3 + 2\pi^2 + 24\log 2 - 24\log^2 2}{324 \cdot 2^{\frac{1}{2}} 3^{\frac{1}{4}}} \frac{1}{\tau^{\frac{10}{3}}} + \ldots$$

RJ, Peschanski; Nakamura, S-J Sin; RJ; RJ, Heller; Heller

- Leading term — perfect fluid behaviour
  second term — 1^{st} order viscous hydrodynamics
  third term — 2^{nd} order viscous hydrodynamics
  fourth term — 3^{rd} order viscous hydrodynamics...
- In general:

$$\varepsilon(\tau) = \sum_{n=2}^{\infty} \frac{\varepsilon_n}{\tau^{\frac{2n}{3}}}$$

- Currently we know 240 terms in this expansion

Heller, RJ, Witaszczyk

- The hydrodynamic series is only asymptotic and has zero radius of convergence...

Heller, RJ, Witaszczyk 1302.0697 [PRL 110 (2013) 211602]

Remarks:

- In order to study far-from equilibrium behaviour for small τ we have to use numerical relativity methods
- We get rid of the dependence on the number of degrees of freedom by parametrizing the energy density through an effective temperature given by

$$\varepsilon(\tau) = \frac{3}{8} N_c^2 \pi^2 T_{eff}^4(\tau)$$

- Previously, we normalized our initial data by setting

$$T_{eff}(\tau = 0) = 1$$

  but this is generically unknown in realistic heavy-ion collisions...
- It is much better to fix the normalization through the hydrodynamic tail...

$$\pi T_{eff}(\tau) \sim \frac{1}{\tau^{\frac{1}{3}}} \text{in the } \tau \to \infty \text{ limit}$$

  The coefficient '1' fixes the units of τ.

Remarks:

- In order to study far-from equilibrium behaviour for small τ we have to use numerical relativity methods
- We get rid of the dependence on the number of degrees of freedom by parametrizing the energy density through an effective temperature given by

$$\varepsilon(\tau) = \frac{3}{8} N_c^2 \pi^2 T_{eff}^4(\tau)$$

- Previously, we normalized our initial data by setting

$$T_{eff}(\tau = 0) = 1$$

  but this is generically unknown in realistic heavy-ion collisions...
- It is much better to fix the normalization through the hydrodynamic tail...

$$\pi T_{eff}(\tau) \sim \frac{1}{\tau^{\frac{1}{3}}} \text{in the } \tau \to \infty \text{ limit}$$

  The coefficient '1' fixes the units of τ.

Remarks:

- In order to study far-from equilibrium behaviour for small τ we have to use numerical relativity methods
- We get rid of the dependence on the number of degrees of freedom by parametrizing the energy density through an effective temperature given by

$$\varepsilon(\tau) = \frac{3}{8} N_c^2 \pi^2 T_{eff}^4(\tau)$$

- Previously, we normalized our initial data by setting

$$T_{eff}(\tau = 0) = 1$$

but this is generically unknown in realistic heavy-ion collisions...

- It is much better to fix the normalization through the hydrodynamic tail...

$$\pi T_{eff}(\tau) \sim \frac{1}{\tau^{\frac{1}{3}}} \text{in the } \tau \to \infty \text{ limit}$$

The coefficient '1' fixes the units of τ.

Remarks:

- In order to study far-from equilibrium behaviour for small τ we have to use numerical relativity methods
- We get rid of the dependence on the number of degrees of freedom by parametrizing the energy density through an effective temperature given by

$$\varepsilon(\tau) = \frac{3}{8} N_c^2 \pi^2 T_{eff}^4(\tau)$$

- Previously, we normalized our initial data by setting

$$T_{eff}(\tau = 0) = 1$$

but this is generically unknown in realistic heavy-ion collisions...

- It is much better to fix the normalization through the hydrodynamic tail...

$$\pi T_{eff}(\tau) \sim \frac{1}{\tau^{\frac{1}{3}}} \text{in the } \tau \to \infty \text{ limit}$$

The coefficient '1' fixes the units of τ.

Remarks:

- In order to study far-from equilibrium behaviour for small τ we have to use numerical relativity methods
- We get rid of the dependence on the number of degrees of freedom by parametrizing the energy density through an effective temperature given by

$$\varepsilon(\tau) = \frac{3}{8} N_c^2 \pi^2 T_{eff}^4(\tau)$$

- Previously, we normalized our initial data by setting

$$T_{eff}(\tau = 0) = 1$$

but this is generically unknown in realistic heavy-ion collisions...

- It is much better to fix the normalization through the hydrodynamic tail...

$$\pi T_{eff}(\tau) \sim \frac{1}{\tau^{\frac{1}{3}}} \text{in the } \tau \to \infty \text{ limit}$$

The coefficient '1' fixes the units of τ.

Remarks:

- In order to study far-from equilibrium behaviour for small τ we have to use numerical relativity methods
- We get rid of the dependence on the number of degrees of freedom by parametrizing the energy density through an effective temperature given by

$$\varepsilon(\tau) = \frac{3}{8} N_c^2 \pi^2 T_{eff}^4(\tau)$$

- Previously, we normalized our initial data by setting

$$T_{eff}(\tau = 0) = 1$$

  but this is generically unknown in realistic heavy-ion collisions...
- It is much better to fix the normalization through the hydrodynamic tail...

$$\pi T_{eff}(\tau) \sim \frac{1}{\tau^{\frac{1}{3}}} \text{in the } \tau \to \infty \text{ limit}$$

  The coefficient '1' fixes the units of τ.

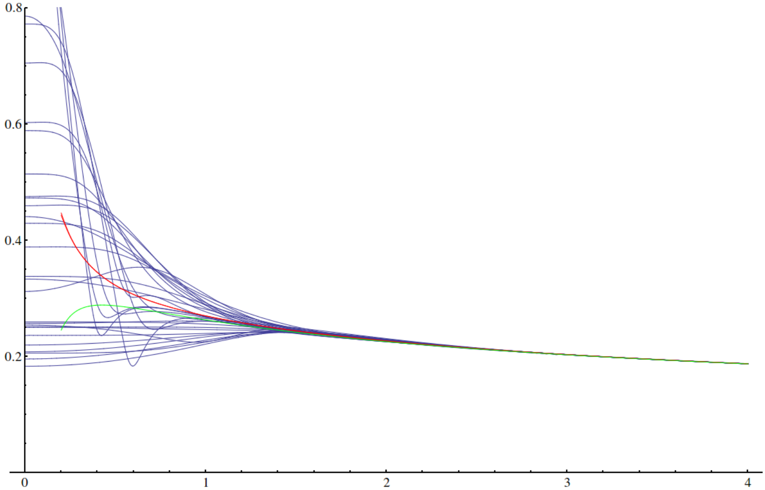
Effective temperature T_{eff} as a function of τ

green line: 3^{rd} order hydro

red line: Borel resummed hydro

- **Very clear transition to a hydrodynamic behaviour**
- Very little information on the initial energy density at $\tau = 0$ (unless we have some specific information on the initial state)

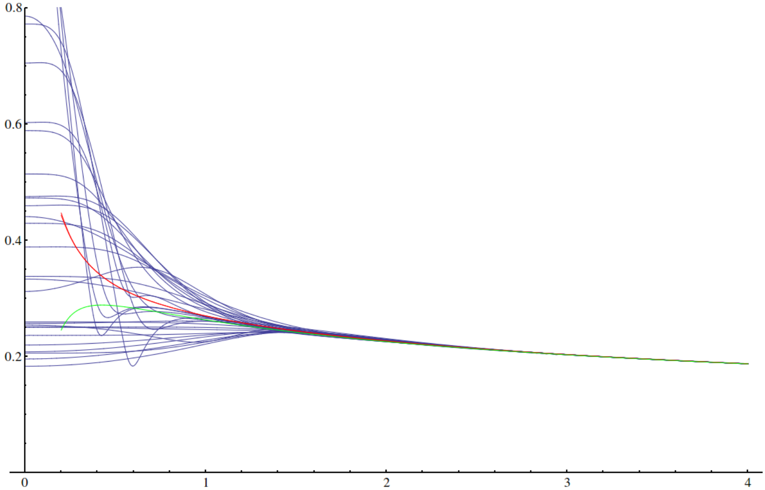
Effective temperature T_{eff} as a function of τ



green line: 3^{rd} order hydro red line: Borel resummed hydro

- **Very clear transition to a hydrodynamic behaviour**
- Very little information on the initial energy density at $\tau = 0$ (unless we have some specific information on the initial state)

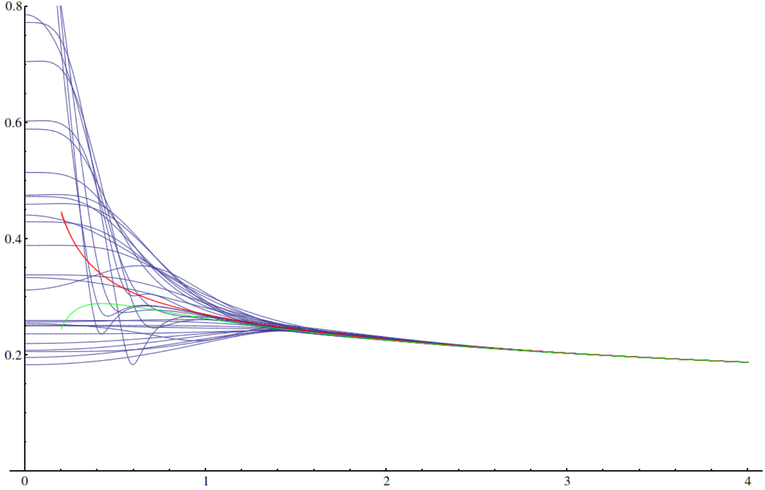
Effective temperature T_{eff} as a function of τ



green line: 3^{rd} order hydro red line: Borel resummed hydro

- **Very clear transition to a hydrodynamic behaviour**
- Very little information on the initial energy density at $\tau = 0$ (unless we have some specific information on the initial state)

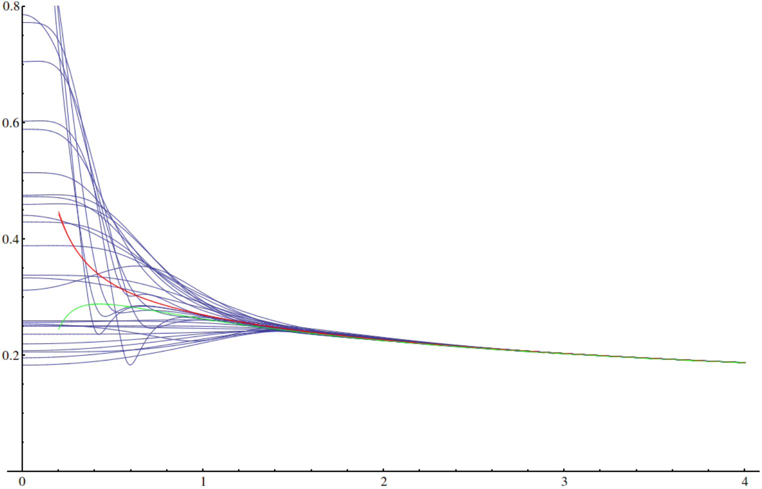
Effective temperature T_{eff} as a function of τ



green line: 3^{rd} order hydro red line: Borel resummed hydro

- **Very clear transition to a hydrodynamic behaviour**
- Very little information on the initial energy density at $\tau = 0$ (unless we have some specific information on the initial state)

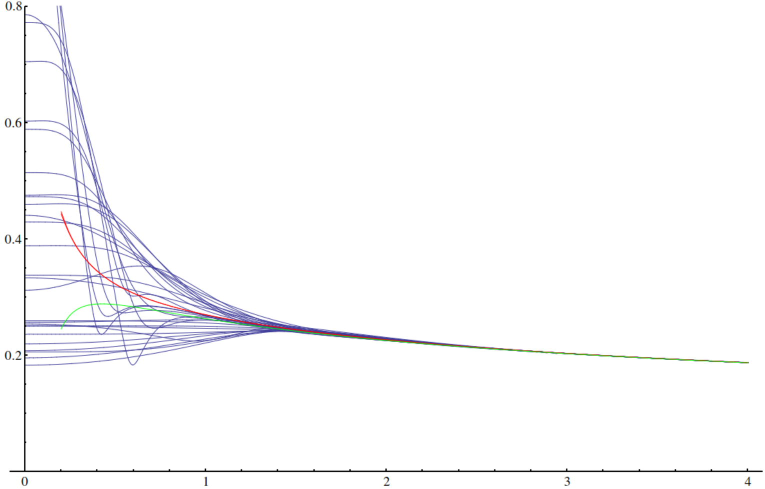
Effective temperature T_{eff} as a function of τ



green line: 3^{rd} order hydro red line: Borel resummed hydro

- **Very clear transition to a hydrodynamic behaviour**
- Very little information on the initial energy density at $\tau = 0$ (unless we have some specific information on the initial state)

Effective temperature T_{eff} as a function of τ



green line: 3^{rd} order hydro red line: Borel resummed hydro

- **Very clear transition to a hydrodynamic behaviour**
- Very little information on the initial energy density at $\tau = 0$ (unless we have some specific information on the initial state)

Transition to hydrodynamics – hydrodynamization

1. Form the dimensionless product $w \equiv T_{eff} \cdot \tau$
2. For all initial conditions considered, *viscous* hydrodynamics works very well for $w \equiv T_{eff} \cdot \tau > 0.7$

   (natural values for RHIC: ($\tau_0 = 0.25\, fm$, $T_0 = 500\, MeV$) assumed in [Broniowski, Chojnacki, Florkowski, Kisiel] correspond to $w = 0.63$)
3. The plasma system is described by *viscous* hydrodynamics even though **it is not in true thermal equilibrium** — there is still a sizable pressure anisotropy

$$\Delta p_L \equiv 1 - \frac{p_L}{\varepsilon/3} \sim 0.7$$

Transition to hydrodynamics – hydrodynamization

1. Form the dimensionless product $w \equiv T_{eff} \cdot \tau$
2. For all initial conditions considered, *viscous* hydrodynamics works very well for $w \equiv T_{eff} \cdot \tau > 0.7$

   (natural values for RHIC: ($\tau_0 = 0.25\,fm$, $T_0 = 500\,MeV$) assumed in [Broniowski, Chojnacki, Florkowski, Kisiel] correspond to $w = 0.63$)
3. The plasma system is described by *viscous* hydrodynamics even though **it is not in true thermal equilibrium** — there is still a sizable pressure anisotropy

$$\Delta p_L \equiv 1 - \frac{p_L}{\varepsilon/3} \sim 0.7$$

Transition to hydrodynamics – hydrodynamization

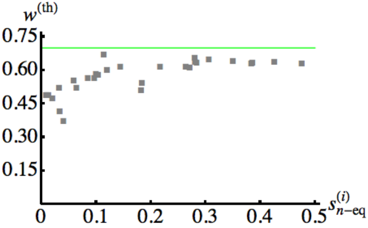
1. Form the dimensionless product $w \equiv T_{eff} \cdot \tau$
2. For all initial conditions considered, *viscous* hydrodynamics works very well for $w \equiv T_{eff} \cdot \tau > 0.7$

   (natural values for RHIC: ($\tau_0 = 0.25\, fm,\ T_0 = 500\, MeV$) assumed in [Broniowski, Chojnacki, Florkowski, Kisiel] correspond to $w = 0.63$)
3. The plasma system is described by *viscous* hydrodynamics even though **it is not in true thermal equilibrium** — there is still a sizable pressure anisotropy

$$\Delta p_L \equiv 1 - \frac{p_L}{\varepsilon/3} \sim 0.7$$

Transition to hydrodynamics – hydrodynamization

1. Form the dimensionless product $w \equiv T_{eff} \cdot \tau$
2. For all initial conditions considered, *viscous* hydrodynamics works very well for $w \equiv T_{eff} \cdot \tau > 0.7$



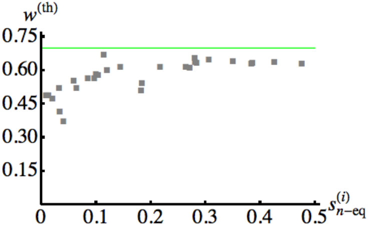
(natural values for RHIC: ($\tau_0 = 0.25\, fm$, $T_0 = 500\, MeV$) assumed in [Broniowski, Chojnacki, Florkowski, Kisiel] correspond to $w = 0.63$)

3. The plasma system is described by *viscous* hydrodynamics even though **it is not in true thermal equilibrium** — there is still a sizable pressure anisotropy

$$\Delta p_L \equiv 1 - \frac{p_L}{\varepsilon/3} \sim 0.7$$

Transition to hydrodynamics – hydrodynamization

1. Form the dimensionless product $w \equiv T_{eff} \cdot \tau$
2. For all initial conditions considered, *viscous* hydrodynamics works very well for $w \equiv T_{eff} \cdot \tau > 0.7$



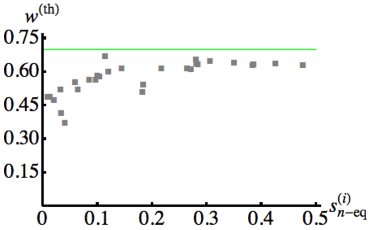
(natural values for RHIC: ($\tau_0 = 0.25\,fm$, $T_0 = 500\,MeV$) assumed in [Broniowski, Chojnacki, Florkowski, Kisiel] correspond to $w = 0.63$)

3. The plasma system is described by *viscous* hydrodynamics even though **it is not in true thermal equilibrium** — there is still a sizable pressure anisotropy

$$\Delta p_L \equiv 1 - \frac{p_L}{\varepsilon/3} \sim 0.7$$

Transition to hydrodynamics – hydrodynamization

1. Form the dimensionless product $w \equiv T_{eff} \cdot \tau$
2. For all initial conditions considered, *viscous* hydrodynamics works very well for $w \equiv T_{eff} \cdot \tau > 0.7$



(natural values for RHIC: ($\tau_0 = 0.25\,fm$, $T_0 = 500\,MeV$) assumed in [Broniowski, Chojnacki, Florkowski, Kisiel] correspond to $w = 0.63$)

3. The plasma system is described by *viscous* hydrodynamics even though **it is not in true thermal equilibrium** — there is still a sizable pressure anisotropy

$$\Delta p_L \equiv 1 - \frac{p_L}{\varepsilon/3} \sim 0.7$$

Key observation:

Hydrodynamization $\neq$ Thermalization

Key observation:

Hydrodynamization $\neq$ **Thermalization**

Role of initial entropy

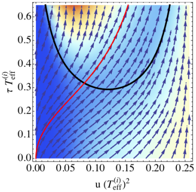
Initial entropy turns out to be a key characterization of the initial state

There is a clear correlation of produced entropy with the initial entropy...

Similar conclusion holds for e.g. *(effective) thermalization time* (understood here as the transition to a viscous hydrodynamic description)

Role of initial entropy

Initial entropy turns out to be a key characterization of the initial state

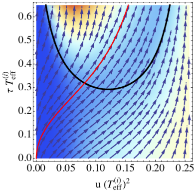


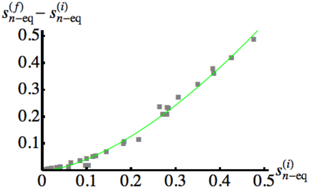
There is a clear correlation of produced entropy with the initial entropy...

Similar conclusion holds for e.g. *(effective) thermalization time* (understood here as the transition to a viscous hydrodynamic description)

Role of initial entropy

Initial entropy turns out to be a key characterization of the initial state



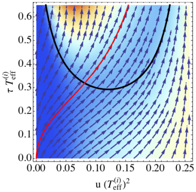


There is a clear correlation of produced entropy with the initial entropy...

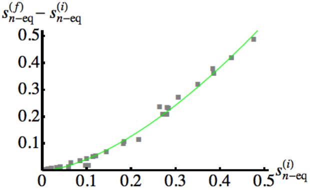
Similar conclusion holds for e.g. *(effective) thermalization time* (understood here as the transition to a viscous hydrodynamic description)

Role of initial entropy

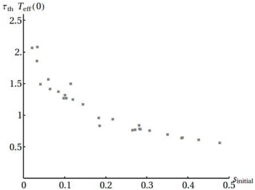
Initial entropy turns out to be a key characterization of the initial state



There is a clear correlation of produced entropy with the initial entropy...



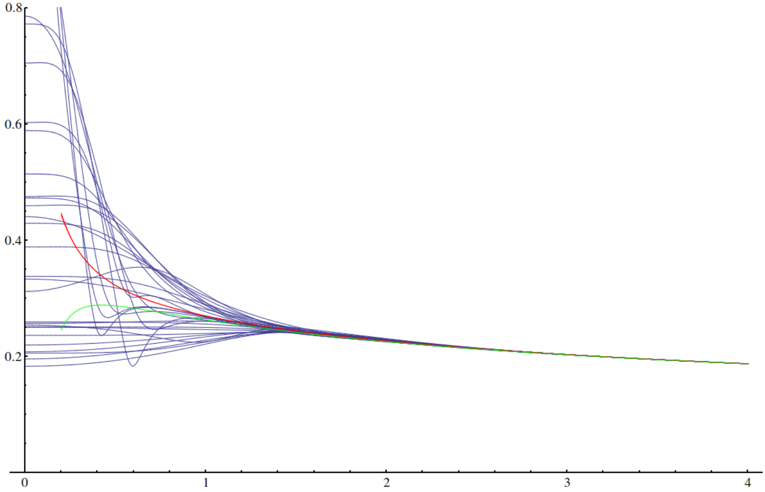
Similar conclusion holds for e.g. *(effective) thermalization time* (understood here as the transition to a viscous hydrodynamic description)



Recall $T_{eff}(\tau)$

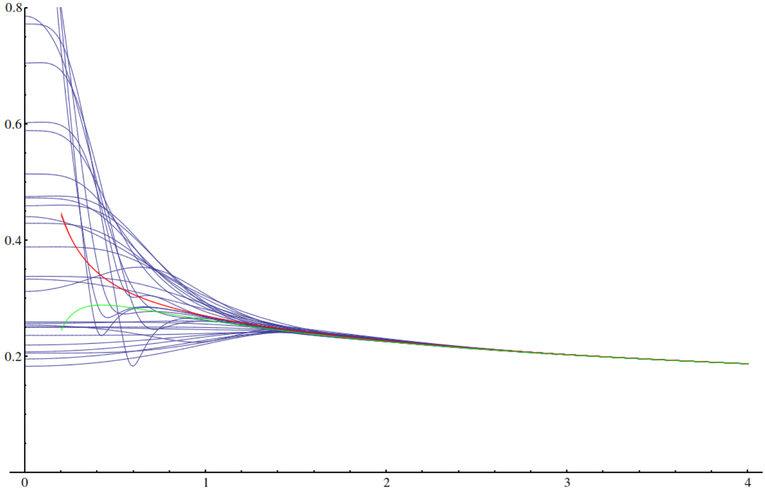
How to model deviations from (all-order) hydrodynamics?

Recall $T_{eff}(\tau)$

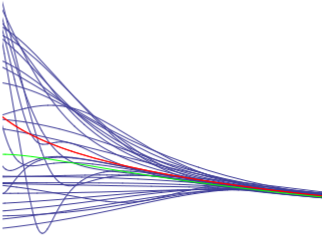


How to model deviations from (all-order) hydrodynamics?

Recall $T_{eff}(\tau)$



How to model deviations from (all-order) hydrodynamics?



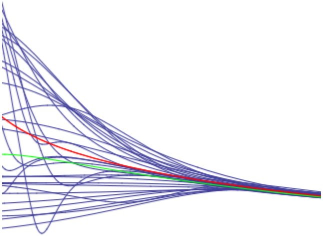
How to model additional non-hydrodynamic degrees of freedom?

- Is there a simple phenomenological model simpler than 5D Einstein's equations??

$$T_{\mu\nu}(T, u^\rho) \quad \sim \quad \text{hydrodynamics}$$
$$T_{\mu\nu}(T, u^\rho, ???) \quad \sim \quad \text{hydrodynamics + additional DOF}$$

  c.f. anisotropic hydrodynamics of Florkowski, Strickland and collaborators

- Can we get information on the possible (number of) degrees of freedom from our knowledge of a) resummed hydrodynamics b) a large set of diverse numerical profiles



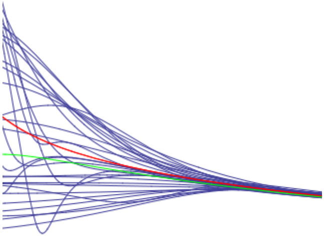
How to model additional non-hydrodynamic degrees of freedom?

- Is there a simple phenomenological model simpler than 5D Einstein's equations??

$$T_{\mu\nu}(T, u^\rho) \quad \sim \quad \text{hydrodynamics}$$
$$T_{\mu\nu}(T, u^\rho, ???) \quad \sim \quad \text{hydrodynamics} + \text{additional DOF}$$

c.f. anisotropic hydrodynamics of Florkowski, Strickland and collaborators

- Can we get information on the possible (number of) degrees of freedom from our knowledge of a) resummed hydrodynamics b) a large set of diverse numerical profiles



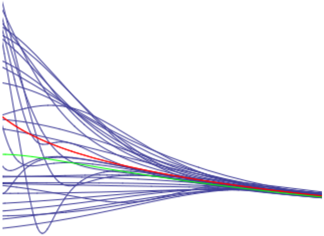
How to model additional non-hydrodynamic degrees of freedom?

- Is there a simple phenomenological model simpler than 5D Einstein's equations??

$$\begin{aligned} T_{\mu\nu}(T, u^\rho) &\sim \text{hydrodynamics} \\ T_{\mu\nu}(T, u^\rho, ???) &\sim \text{hydrodynamics} + \text{additional DOF} \end{aligned}$$

c.f. anisotropic hydrodynamics of Florkowski, Strickland and collaborators

- Can we get information on the possible (number of) degrees of freedom from our knowledge of a) resummed hydrodynamics b) a large set of diverse numerical profiles



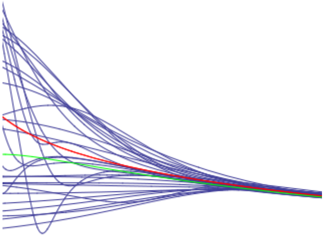
How to model additional non-hydrodynamic degrees of freedom?

- Is there a simple phenomenological model simpler than 5D Einstein's equations??

$$
\begin{aligned}
T_{\mu\nu}(T, u^\rho) &\sim \text{hydrodynamics} \\
T_{\mu\nu}(T, u^\rho, ???) &\sim \text{hydrodynamics} + \text{additional DOF}
\end{aligned}
$$

  c.f. anisotropic hydrodynamics of Florkowski, Strickland and collaborators

- Can we get information on the possible (number of) degrees of freedom from our knowledge of a) resummed hydrodynamics b) a large set of diverse numerical profiles



How to model additional non-hydrodynamic degrees of freedom?

- Is there a simple phenomenological model simpler than 5D Einstein's equations??

$$\begin{aligned} T_{\mu\nu}(T, u^\rho) &\sim \text{hydrodynamics} \\ T_{\mu\nu}(T, u^\rho, ???) &\sim \text{hydrodynamics} + \text{additional DOF} \end{aligned}$$

  c.f. anisotropic hydrodynamics of Florkowski, Strickland and collaborators

- Can we get information on the possible (number of) degrees of freedom from our knowledge of a) resummed hydrodynamics b) a large set of diverse numerical profiles

Quasinormal modes

- On the gravity side, deviations from hydrodynamics may be represented by metric perturbations (quasinormal modes)
- Each quasinormal mode represents an independent degree of freedom from the 4D perspective...
- The generic structure of QNM modes for a boost-invariant flow (including first viscous corrections)

$$\delta\varepsilon(\tau) \sim \tau^{-2} e^{-i\omega_{QNM}\int \pi T(\tau) d\tau}$$

  where $\omega_{QNM} = \omega_R - i\omega_I$
- One can estimate that $s = \int_0^\tau \pi T(\tau) d\tau$ at the transition to hydrodynamics would set the scale for how many QNM would be relevant there...
- It turns out that $s = 1.6...3$ and $Im\ \omega_{QNM} = 2.75, 4.76, 6.77, ...$
- A few additional DOF might suffice?

Quasinormal modes

- On the gravity side, deviations from hydrodynamics may be represented by metric perturbations (quasinormal modes)
- Each quasinormal mode represents an independent degree of freedom from the 4D perspective...
- The generic structure of QNM modes for a boost-invariant flow (including first viscous corrections)

$$\delta\varepsilon(\tau) \sim \tau^{-2} e^{-i\omega_{QNM} \int \pi T(\tau) d\tau}$$

  where $\omega_{QNM} = \omega_R - i\omega_I$
- One can estimate that $s = \int_0^\tau \pi T(\tau) d\tau$ at the transition to hydrodynamics would set the scale for how many QNM would be relevant there...
- It turns out that $s = 1.6...3$ and $Im\ \omega_{QNM} = 2.75, 4.76, 6.77, ...$
- A few additional DOF might suffice?

Quasinormal modes

- On the gravity side, deviations from hydrodynamics may be represented by metric perturbations (quasinormal modes)
- Each quasinormal mode represents an independent degree of freedom from the 4D perspective...
- The generic structure of QNM modes for a boost-invariant flow (including first viscous corrections)

$$\delta\varepsilon(\tau) \sim \tau^{-2} e^{-i\omega_{QNM} \int \pi T(\tau) d\tau}$$

where $\omega_{QNM} = \omega_R - i\omega_I$

- One can estimate that $s = \int_0^\tau \pi T(\tau) d\tau$ at the transition to hydrodynamics would set the scale for how many QNM would be relevant there...
- It turns out that $s = 1.6 \ldots 3$ and $Im\ \omega_{QNM} = 2.75, 4.76, 6.77, \ldots$
- A few additional DOF might suffice?

Quasinormal modes

- On the gravity side, deviations from hydrodynamics may be represented by metric perturbations (quasinormal modes)
- Each quasinormal mode represents an independent degree of freedom from the 4D perspective...
- The generic structure of QNM modes for a boost-invariant flow (including first viscous corrections)

$$\delta\varepsilon(\tau) \sim \tau^{-2} e^{-i\omega_{QNM} \int \pi T(\tau) d\tau}$$

where $\omega_{QNM} = \omega_R - i\omega_I$

- One can estimate that $s = \int_0^\tau \pi T(\tau) d\tau$ at the transition to hydrodynamics would set the scale for how many QNM would be relevant there...
- It turns out that $s = 1.6 \dots 3$ and $Im\ \omega_{QNM} = 2.75, 4.76, 6.77, \dots$
- A few additional DOF might suffice?

Quasinormal modes

- On the gravity side, deviations from hydrodynamics may be represented by metric perturbations (quasinormal modes)
- Each quasinormal mode represents an independent degree of freedom from the 4D perspective...
- The generic structure of QNM modes for a boost-invariant flow (including first viscous corrections)

$$\delta\varepsilon(\tau) \sim \tau^{-2} e^{-i\omega_{QNM} \int \pi T(\tau) d\tau}$$

where $\omega_{QNM} = \omega_R - i\omega_I$

- One can estimate that $s = \int_0^\tau \pi T(\tau) d\tau$ at the transition to hydrodynamics would set the scale for how many QNM would be relevant there...
- It turns out that $s = 1.6...3$ and $Im\ \omega_{QNM} = 2.75, 4.76, 6.77, \ldots$
- A few additional DOF might suffice?

Quasinormal modes

- On the gravity side, deviations from hydrodynamics may be represented by metric perturbations (quasinormal modes)
- Each quasinormal mode represents an independent degree of freedom from the 4D perspective...
- The generic structure of QNM modes for a boost-invariant flow (including first viscous corrections)

$$\delta\varepsilon(\tau) \sim \tau^{-2} e^{-i\omega_{QNM}\int \pi T(\tau)d\tau}$$

where $\omega_{QNM} = \omega_R - i\omega_I$
- One can estimate that $s = \int_0^\tau \pi T(\tau)d\tau$ at the transition to hydrodynamics would set the scale for how many QNM would be relevant there...
- It turns out that $s = 1.6...3$ and $Im\ \omega_{QNM} = 2.75, 4.76, 6.77, ...$
- A few additional DOF might suffice?

Quasinormal modes

- On the gravity side, deviations from hydrodynamics may be represented by metric perturbations (quasinormal modes)
- Each quasinormal mode represents an independent degree of freedom from the 4D perspective...
- The generic structure of QNM modes for a boost-invariant flow (including first viscous corrections)

$$\delta\varepsilon(\tau) \sim \tau^{-2} e^{-i\omega_{QNM} \int \pi T(\tau) d\tau}$$

where $\omega_{QNM} = \omega_R - i\omega_I$

- One can estimate that $s = \int_0^\tau \pi T(\tau) d\tau$ at the transition to hydrodynamics would set the scale for how many QNM would be relevant there...
- It turns out that $s = 1.6 \ldots 3$ and $Im\ \omega_{QNM} = 2.75, 4.76, 6.77, \ldots$
- A few additional DOF might suffice?

How to write an equation of motion for a scalar nonhydrodynamic degree of freedom (e.g. $\mathrm{tr}\, F^2$) in a generic hydrodynamic background?

- The scalar dof corresponds to a scalar QNM with frequencies $\omega_{QNM} = \omega_R - i\omega_I$
- **Key feature:** the frequencies have only very mild dependence on the spatial momentum — the dynamics seems 'ultralocal'
- We may write the equation of motion in a generic hydrodynamic flow

$$\mathcal{D}^2\phi + 2\omega_I \mathcal{D}\phi + \left(\omega_I^2 + \omega_R^2\right)\phi = 0$$

where

$$\mathcal{D} \equiv \frac{1}{T} u^\mu \partial_\mu$$

Extension to nonhydrodynamic modes of $T_{\mu\nu}$ in progress...

How to write an equation of motion for a scalar nonhydrodynamic degree of freedom (e.g. $\mathrm{tr}\, F^2$) in a generic hydrodynamic background?

- The scalar dof corresponds to a scalar QNM with frequencies $\omega_{QNM} = \omega_R - i\omega_I$
- **Key feature:** the frequencies have only very mild dependence on the spatial momentum — the dynamics seems 'ultralocal'
- We may write the equation of motion in a generic hydrodynamic flow

$$\mathcal{D}^2\phi + 2\omega_I \mathcal{D}\phi + \left(\omega_I^2 + \omega_R^2\right)\phi = 0$$

where

$$\mathcal{D} \equiv \frac{1}{T} u^\mu \partial_\mu$$

Extension to nonhydrodynamic modes of $T_{\mu\nu}$ in progress...

How to write an equation of motion for a scalar nonhydrodynamic degree of freedom (e.g. $\operatorname{tr} F^2$) in a generic hydrodynamic background?

- The scalar dof corresponds to a scalar QNM with frequencies $\omega_{QNM} = \omega_R - i\omega_I$
- **Key feature:** the frequencies have only very mild dependence on the spatial momentum — the dynamics seems 'ultralocal'
- We may write the equation of motion in a generic hydrodynamic flow

$$\mathcal{D}^2\phi + 2\omega_I \mathcal{D}\phi + \left(\omega_I^2 + \omega_R^2\right)\phi = 0$$

where

$$\mathcal{D} \equiv \frac{1}{T} u^\mu \partial_\mu$$

Extension to nonhydrodynamic modes of $T_{\mu\nu}$ in progress...

How to write an equation of motion for a scalar nonhydrodynamic degree of freedom (e.g. $\mathrm{tr}\, F^2$) in a generic hydrodynamic background?

- The scalar dof corresponds to a scalar QNM with frequencies $\omega_{QNM} = \omega_R - i\omega_I$
- **Key feature:** the frequencies have only very mild dependence on the spatial momentum — the dynamics seems 'ultralocal'
- We may write the equation of motion in a generic hydrodynamic flow

$$\mathcal{D}^2\phi + 2\omega_I \mathcal{D}\phi + \left(\omega_I^2 + \omega_R^2\right)\phi = 0$$

where

$$\mathcal{D} \equiv \frac{1}{T} u^\mu \partial_\mu$$

Extension to nonhydrodynamic modes of $T_{\mu\nu}$ in progress...

How to write an equation of motion for a scalar nonhydrodynamic degree of freedom (e.g. $\mathrm{tr}\, F^2$) in a generic hydrodynamic background?

- The scalar dof corresponds to a scalar QNM with frequencies $\omega_{QNM} = \omega_R - i\omega_I$
- **Key feature:** the frequencies have only very mild dependence on the spatial momentum — the dynamics seems 'ultralocal'
- We may write the equation of motion in a generic hydrodynamic flow

$$\mathcal{D}^2\phi + 2\omega_I \mathcal{D}\phi + \left(\omega_I^2 + \omega_R^2\right)\phi = 0$$

where

$$\mathcal{D} \equiv \frac{1}{T} u^\mu \partial_\mu$$

Extension to nonhydrodynamic modes of $T_{\mu\nu}$ in progress...

How to write an equation of motion for a scalar nonhydrodynamic degree of freedom (e.g. $\operatorname{tr} F^2$) in a generic hydrodynamic background?

- The scalar dof corresponds to a scalar QNM with frequencies $\omega_{QNM} = \omega_R - i\omega_I$
- **Key feature:** the frequencies have only very mild dependence on the spatial momentum — the dynamics seems 'ultralocal'
- We may write the equation of motion in a generic hydrodynamic flow

$$\mathcal{D}^2\phi + 2\omega_I \mathcal{D}\phi + \left(\omega_I^2 + \omega_R^2\right)\phi = 0$$

where

$$\mathcal{D} \equiv \frac{1}{T} u^\mu \partial_\mu$$

Extension to nonhydrodynamic modes of $T_{\mu\nu}$ in progress...

How to write an equation of motion for a scalar nonhydrodynamic degree of freedom (e.g. $\mathrm{tr}\, F^2$) in a generic hydrodynamic background?

- The scalar dof corresponds to a scalar QNM with frequencies $\omega_{QNM} = \omega_R - i\omega_I$
- **Key feature:** the frequencies have only very mild dependence on the spatial momentum — the dynamics seems 'ultralocal'
- We may write the equation of motion in a generic hydrodynamic flow

$$\mathcal{D}^2\phi + 2\omega_I \mathcal{D}\phi + \left(\omega_I^2 + \omega_R^2\right)\phi = 0$$

where

$$\mathcal{D} \equiv \frac{1}{T} u^\mu \partial_\mu$$

Extension to nonhydrodynamic modes of $T_{\mu\nu}$ in progress...

Conclusions

- AdS/CFT provides a very general framework for studying time-dependent dynamical processes
- The AdS/CFT methods *do not* presuppose hydrodynamics so are applicable even to very out-of-equilibrium configurations
- AdS/CFT may fill in gaps in our knowledge of the early nonequilibrium stage of plasma evolution
- Thermalization $\neq$ hydrodynamization
- Simple dimensionless criterion for applicability of hydrodynamics
- Important role of 'initial entropy' as a characterization of the initial state
- One can perhaps understand better the dynamics of lowest nonhydrodynamic degrees of freedom from the 4D perspective
- Key role of quasinormal frequencies...

Conclusions

- AdS/CFT provides a very general framework for studying time-dependent dynamical processes
- The AdS/CFT methods *do not* presuppose hydrodynamics so are applicable even to very out-of-equilibrium configurations
- AdS/CFT may fill in gaps in our knowledge of the early nonequilibrium stage of plasma evolution
- Thermalization $\neq$ hydrodynamization
- Simple dimensionless criterion for applicability of hydrodynamics
- Important role of 'initial entropy' as a characterization of the initial state
- One can perhaps understand better the dynamics of lowest nonhydrodynamic degrees of freedom from the 4D perspective
- Key role of quasinormal frequencies...

Conclusions

- AdS/CFT provides a very general framework for studying time-dependent dynamical processes
- The AdS/CFT methods *do not* presuppose hydrodynamics so are applicable even to very out-of-equilibrium configurations
- AdS/CFT may fill in gaps in our knowledge of the early nonequilibrium stage of plasma evolution
- Thermalization $\neq$ hydrodynamization
- Simple dimensionless criterion for applicability of hydrodynamics
- Important role of 'initial entropy' as a characterization of the initial state
- One can perhaps understand better the dynamics of lowest nonhydrodynamic degrees of freedom from the 4D perspective
- Key role of quasinormal frequencies...

Conclusions

- AdS/CFT provides a very general framework for studying time-dependent dynamical processes
- The AdS/CFT methods *do not* presuppose hydrodynamics so are applicable even to very out-of-equilibrium configurations
- AdS/CFT may fill in gaps in our knowledge of the early nonequilibrium stage of plasma evolution
- Thermalization $\neq$ hydrodynamization
- Simple dimensionless criterion for applicability of hydrodynamics
- Important role of 'initial entropy' as a characterization of the initial state
- One can perhaps understand better the dynamics of lowest nonhydrodynamic degrees of freedom from the 4D perspective
- Key role of quasinormal frequencies...

Conclusions

- AdS/CFT provides a very general framework for studying time-dependent dynamical processes
- The AdS/CFT methods *do not* presuppose hydrodynamics so are applicable even to very out-of-equilibrium configurations
- AdS/CFT may fill in gaps in our knowledge of the early nonequilibrium stage of plasma evolution
- Thermalization $\neq$ hydrodynamization
- Simple dimensionless criterion for applicability of hydrodynamics
- Important role of 'initial entropy' as a characterization of the initial state
- One can perhaps understand better the dynamics of lowest nonhydrodynamic degrees of freedom from the 4D perspective
- Key role of quasinormal frequencies...

Conclusions

- AdS/CFT provides a very general framework for studying time-dependent dynamical processes
- The AdS/CFT methods *do not* presuppose hydrodynamics so are applicable even to very out-of-equilibrium configurations
- AdS/CFT may fill in gaps in our knowledge of the early nonequilibrium stage of plasma evolution
- Thermalization $\neq$ hydrodynamization
- Simple dimensionless criterion for applicability of hydrodynamics
- Important role of 'initial entropy' as a characterization of the initial state
- One can perhaps understand better the dynamics of lowest nonhydrodynamic degrees of freedom from the 4D perspective
- Key role of quasinormal frequencies...

Conclusions

- AdS/CFT provides a very general framework for studying time-dependent dynamical processes
- The AdS/CFT methods *do not* presuppose hydrodynamics so are applicable even to very out-of-equilibrium configurations
- AdS/CFT may fill in gaps in our knowledge of the early nonequilibrium stage of plasma evolution
- Thermalization $\neq$ hydrodynamization
- Simple dimensionless criterion for applicability of hydrodynamics
- Important role of 'initial entropy' as a characterization of the initial state
- One can perhaps understand better the dynamics of lowest nonhydrodynamic degrees of freedom from the 4D perspective
- Key role of quasinormal frequencies...

Conclusions

- AdS/CFT provides a very general framework for studying time-dependent dynamical processes
- The AdS/CFT methods *do not* presuppose hydrodynamics so are applicable even to very out-of-equilibrium configurations
- AdS/CFT may fill in gaps in our knowledge of the early nonequilibrium stage of plasma evolution
- Thermalization $\neq$ hydrodynamization
- Simple dimensionless criterion for applicability of hydrodynamics
- Important role of 'initial entropy' as a characterization of the initial state
- One can perhaps understand better the dynamics of lowest nonhydrodynamic degrees of freedom from the 4D perspective
- Key role of quasinormal frequencies...

Conclusions

- AdS/CFT provides a very general framework for studying time-dependent dynamical processes
- The AdS/CFT methods *do not* presuppose hydrodynamics so are applicable even to very out-of-equilibrium configurations
- AdS/CFT may fill in gaps in our knowledge of the early nonequilibrium stage of plasma evolution
- Thermalization $\neq$ hydrodynamization
- Simple dimensionless criterion for applicability of hydrodynamics
- Important role of 'initial entropy' as a characterization of the initial state
- One can perhaps understand better the dynamics of lowest nonhydrodynamic degrees of freedom from the 4D perspective
- Key role of quasinormal frequencies...