# Numerical Relativity in AdS, Holography and Thermalization

Christian Ecker

Institute for Theoretical Physics
Vienna University of Technology
Wiedner Hauptstrasse 8-10/136 1040 Vienna, (Austria)

*christian.ecker@tuwien.ac.at*

September 24, 2014

# Introduction

- **Motivation**
  - Quark-gluon plasma (QGP) produced at RHIC and LHC behaves like a strongly coupled liquid.
  - Thermalization happens on a small time scale ($\leq 1fm/c \approx 100ns$).
  - **Question**: What are the mechanisms responsible for the fast thermalization?

- **Complications**
  - Due to strong coupling perturbative QCD is not applicable.
  - Time dependent processes are problematic for lattice QCD.

- **AdS/CFT approach**
  - Employ AdS/CFT to study dynamics of $\mathcal{N} = 4$ SYM theory.
  - Dynamics of 4-dim. QFT is mapped to class. gravity on 5-dim. AdS.
  - QFT observables we use to study thermalization are the energy momentum tensor, two-point functions and entanglement entropy.
  - On the gravity side these observables can be computed from the metric, from geodesics and from extremal surfaces.

# Introduction

- **Motivation**
  - Quark-gluon plasma (QGP) produced at RHIC and LHC behaves like a strongly coupled liquid.
  - Thermalization happens on a small time scale ($\leq 1 fm/c \approx 100 ns$).
  - **Question**: What are the mechanisms responsible for the fast thermalization?

- **Complications**
  - Due to strong coupling perturbative QCD is not applicable.
  - Time dependent processes are problematic for lattice QCD.

- **AdS/CFT approach**
  - Employ AdS/CFT to study dynamics of $\mathcal{N} = 4$ SYM theory.
  - Dynamics of 4-dim. QFT is mapped to class. gravity on 5-dim. AdS.
  - QFT observables we use to study thermalization are the energy momentum tensor, two-point functions and entanglement entropy.
  - On the gravity side these observables can be computed from the metric, from geodesics and from extremal surfaces.

# Introduction

- **Motivation**
  - Quark-gluon plasma (QGP) produced at RHIC and LHC behaves like a strongly coupled liquid.
  - Thermalization happens on a small time scale ($\leq 1 fm/c \approx 100 ns$).
  - **Question**: What are the mechanisms responsible for the fast thermalization?

- **Complications**
  - Due to strong coupling perturbative QCD is not applicable.
  - Time dependent processes are problematic for lattice QCD.

- **AdS/CFT approach**
  - Employ AdS/CFT to study dynamics of $\mathcal{N} = 4$ SYM theory.
  - Dynamics of 4-dim. QFT is mapped to class. gravity on 5-dim. AdS.
  - QFT observables we use to study thermalization are the energy momentum tensor, two-point functions and entanglement entropy.
  - On the gravity side these observables can be computed from the metric, from geodesics and from extremal surfaces.

# Introduction

- **Motivation**
  - Quark-gluon plasma (QGP) produced at RHIC and LHC behaves like a strongly coupled liquid.
  - Thermalization happens on a small time scale ($\lesssim 1 fm/c \approx 100 ns$).
  - **Question**: What are the mechanisms responsible for the fast thermalization?

- **Complications**
  - Due to strong coupling perturbative QCD is not applicable.
  - Time dependent processes are problematic for lattice QCD.

- **AdS/CFT approach**
  - Employ AdS/CFT to study dynamics of $\mathcal{N} = 4$ SYM theory.
  - Dynamics of 4-dim. QFT is mapped to class. gravity on 5-dim. AdS.
  - QFT observables we use to study thermalization are the energy momentum tensor, two-point functions and entanglement entropy.
  - On the gravity side these observables can be computed from the metric, from geodesics and from extremal surfaces.

# Introduction

- **Motivation**
  - Quark-gluon plasma (QGP) produced at RHIC and LHC behaves like a strongly coupled liquid.
  - Thermalization happens on a small time scale ($\lesssim 1 fm/c \approx 100 ns$).
  - **Question**: What are the mechanisms responsible for the fast thermalization?

- **Complications**
  - Due to strong coupling perturbative QCD is not applicable.
  - Time dependent processes are problematic for lattice QCD.

- **AdS/CFT approach**
  - Employ AdS/CFT to study dynamics of $\mathcal{N} = 4$ SYM theory.
  - Dynamics of 4-dim. QFT is mapped to class. gravity on 5-dim. AdS.
  - QFT observables we use to study thermalization are the energy momentum tensor, two-point functions and entanglement entropy.
  - On the gravity side these observables can be computed from the metric, from geodesics and from extremal surfaces.

# Introduction

## Motivation

- Quark-gluon plasma (QGP) produced at RHIC and LHC behaves like a strongly coupled liquid.
- Thermalization happens on a small time scale ($\leq 1 fm/c \approx 100 ns$).
- **Question**: What are the mechanisms responsible for the fast thermalization?

## Complications

- Due to strong coupling perturbative QCD is not applicable.
- Time dependent processes are problematic for lattice QCD.

## AdS/CFT approach

- Employ AdS/CFT to study dynamics of $\mathcal{N} = 4$ SYM theory.
- Dynamics of 4-dim. QFT is mapped to class. gravity on 5-dim. AdS.
- QFT observables we use to study thermalization are the energy momentum tensor, two-point functions and entanglement entropy.
- On the gravity side these observables can be computed from the metric, from geodesics and from extremal surfaces.

# Introduction

- **Motivation**
  - Quark-gluon plasma (QGP) produced at RHIC and LHC behaves like a strongly coupled liquid.
  - Thermalization happens on a small time scale ($\leq 1 fm/c \approx 100 ns$).
  - **Question**: What are the mechanisms responsible for the fast thermalization?
- **Complications**
  - Due to strong coupling perturbative QCD is not applicable.
  - Time dependent processes are problematic for lattice QCD.
- **AdS/CFT approach**
  - Employ AdS/CFT to study dynamics of $\mathcal{N} = 4$ SYM theory.
  - Dynamics of 4-dim. QFT is mapped to class. gravity on 5-dim. AdS.
  - QFT observables we use to study thermalization are the energy momentum tensor, two-point functions and entanglement entropy.
  - On the gravity side these observables can be computed from the metric, from geodesics and from extremal surfaces.

# Introduction

- **Motivation**
  - Quark-gluon plasma (QGP) produced at RHIC and LHC behaves like a strongly coupled liquid.
  - Thermalization happens on a small time scale ($\lesssim 1 fm/c \approx 100 ns$).
  - **Question**: What are the mechanisms responsible for the fast thermalization?

- **Complications**
  - Due to strong coupling perturbative QCD is not applicable.
  - Time dependent processes are problematic for lattice QCD.

- **AdS/CFT approach**
  - Employ AdS/CFT to study dynamics of $\mathcal{N} = 4$ SYM theory.
  - Dynamics of 4-dim. QFT is mapped to class. gravity on 5-dim. AdS.
  - QFT observables we use to study thermalization are the energy momentum tensor, two-point functions and entanglement entropy.
  - On the gravity side these observables can be computed from the metric, from geodesics and from extremal surfaces.

# Introduction

- **Motivation**
  - Quark-gluon plasma (QGP) produced at RHIC and LHC behaves like a strongly coupled liquid.
  - Thermalization happens on a small time scale ($\lesssim 1 fm/c \approx 100 ns$).
  - **Question**: What are the mechanisms responsible for the fast thermalization?

- **Complications**
  - Due to strong coupling perturbative QCD is not applicable.
  - Time dependent processes are problematic for lattice QCD.

- **AdS/CFT approach**
  - Employ AdS/CFT to study dynamics of $\mathcal{N} = 4$ SYM theory.
  - Dynamics of 4-dim. QFT is mapped to class. gravity on 5-dim. AdS.
  - QFT observables we use to study thermalization are the energy momentum tensor, two-point functions and entanglement entropy.
  - On the gravity side these observables can be computed from the metric, from geodesics and from extremal surfaces.

# Introduction

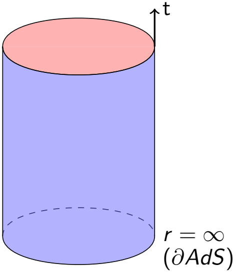
- **Motivation**
  - Quark-gluon plasma (QGP) produced at RHIC and LHC behaves like a strongly coupled liquid.
  - Thermalization happens on a small time scale ($\leq 1 fm/c \approx 100 ns$).
  - **Question**: What are the mechanisms responsible for the fast thermalization?

- **Complications**
  - Due to strong coupling perturbative QCD is not applicable.
  - Time dependent processes are problematic for lattice QCD.

- **AdS/CFT approach**
  - Employ AdS/CFT to study dynamics of $\mathcal{N} = 4$ SYM theory.
  - Dynamics of 4-dim. QFT is mapped to class. gravity on 5-dim. AdS.
  - QFT observables we use to study thermalization are the energy momentum tensor, two-point functions and entanglement entropy.
  - On the gravity side these observables can be computed from the metric, from geodesics and from extremal surfaces.

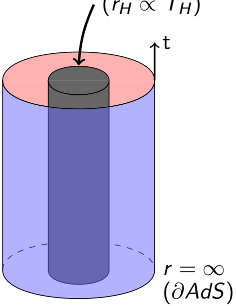
# Anti-de Sitter spacetime and the AdS/CFT correspondence

- Anti-de Sitter spacetime
  - Solution of vacuum Einstein equations with negative $\Lambda$.
  - Boundary at $r = \infty$.



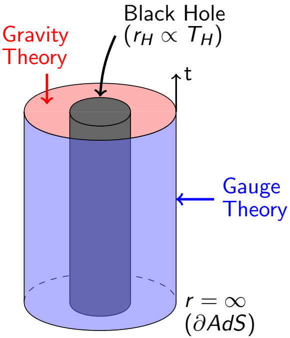
# Anti-de Sitter spacetime and the AdS/CFT correspondence

- Anti-de Sitter spacetime
  - Solution of vacuum Einstein equations with negative $\Lambda$.
  - Boundary at $r = \infty$.
- Asymptotic anti-de Sitter spacetimes
  - "look" near $r = \infty$ like AdS.
  - e.g.: AdS-black hole
  - BH-temperature $T_H \propto$ horizon radius $r_H$.



# Anti-de Sitter spacetime and the AdS/CFT correspondence

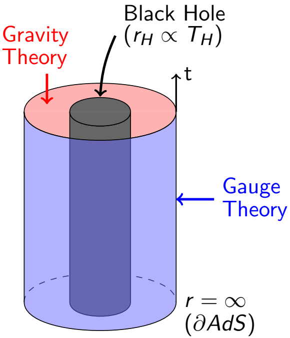
- Anti-de Sitter spacetime
  - Solution of vacuum Einstein equations with negative $\Lambda$.
  - Boundary at $r = \infty$.
- Asymptotic anti-de Sitter spacetimes
  - "look" near $r = \infty$ like AdS.
  - e.g.: AdS-black hole
  - BH-temperature $T_H \propto$ horizon radius $r_H$.




- AdS/CFT correspondence
  Classical gravity on $AdS_5 \leftrightarrow$ strongly-coupled $\mathcal{N} = 4$ SYM on $\partial AdS_5$

# Anti-de Sitter spacetime and the AdS/CFT correspondence

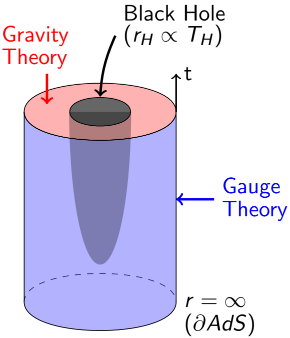
- Anti-de Sitter spacetime
  - Solution of vacuum Einstein equations with negative $\Lambda$.
  - Boundary at $r = \infty$.
- Asymptotic anti-de Sitter spacetimes
  - "look" near $r = \infty$ like AdS.
  - e.g.: AdS-black hole
  - BH-temperature $T_H \propto$ horizon radius $r_H$.




- AdS/CFT correspondence
  Classical gravity on $AdS_5 \leftrightarrow$ strongly-coupled $\mathcal{N} = 4$ SYM on $\partial AdS_5$
- At finite temperature:
  $AdS_5$-BH $\leftrightarrow$ strongly-coupled $\mathcal{N} = 4$ SYM at $T = T_H$.

# Anti-de Sitter spacetime and the AdS/CFT correspondence

- Anti-de Sitter spacetime
  - Solution of vacuum Einstein equations with negative $\Lambda$.
  - Boundary at $r = \infty$.
- Asymptotic anti-de Sitter spacetimes
  - "look" near $r = \infty$ like AdS.
  - e.g.: AdS-black hole
  - BH-temperature $T_H \propto$ horizon radius $r_H$.

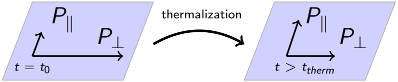



- AdS/CFT correspondence
  Classical gravity on $AdS_5 \leftrightarrow$ strongly-coupled $\mathcal{N} = 4$ SYM on $\partial AdS_5$
- At finite temperature:
  $AdS_5$-BH $\leftrightarrow$ strongly-coupled $\mathcal{N} = 4$ SYM at $T = T_H$.
- Black hole formation in AdS $\leftrightarrow$ thermalization in gauge theory.

# Thermalization of $\mathcal{N} = 4$ SYM Plasma

Energy momentum tensor (EMT) of the anisotropic SYM-plasma:

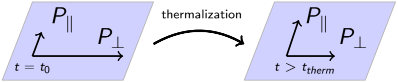
$$T_{\mu\nu} \propto \mathrm{diag}\left[\epsilon, P_{\parallel}(t), \underbrace{P_{\perp}(t), P_{\perp}(t)}_{O(2)}\right]$$



# Thermalization of $\mathcal{N} = 4$ SYM Plasma

Energy momentum tensor (EMT) of the anisotropic SYM-plasma:

$$T_{\mu\nu} \propto \mathrm{diag}\big[\epsilon, P_{\|}(t), \underbrace{P_{\perp}(t), P_{\perp}(t)}_{O(2)}\big]$$

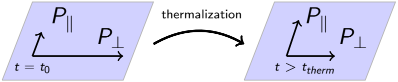



AdS/CFT relates $T_{\mu\nu}$ to the metric of an anisotropic AdS-BH.

# Thermalization of $\mathcal{N} = 4$ SYM Plasma

Energy momentum tensor (EMT) of the anisotropic SYM-plasma:

$$T_{\mu\nu} \propto \mathrm{diag}\big[\epsilon, P_{\|}(t), \underbrace{P_{\perp}(t), P_{\perp}(t)}_{O(2)}\big]$$




AdS/CFT relates $T_{\mu\nu}$ to the metric of an anisotropic AdS-BH.

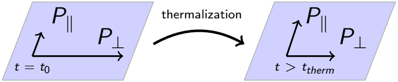
Line element in Eddington-Finkelstein coordinates:

$$ds^2 = 2drdt - A(r,t)dt^2 + \Sigma(r,t)^2\big(e^{-2B(r,t)}dx_{\|}^2 + \underbrace{e^{B(r,t)}d\vec{x}_{\perp}^2}_{O(2)}\big)$$

# Thermalization of $\mathcal{N} = 4$ SYM Plasma

Energy momentum tensor (EMT) of the anisotropic SYM-plasma:

$$T_{\mu\nu} \propto \mathrm{diag}\left[\epsilon, P_{\parallel}(t), \underbrace{P_{\perp}(t), P_{\perp}(t)}_{O(2)}\right]$$




AdS/CFT relates $T_{\mu\nu}$ to the metric of an anisotropic AdS-BH.

Line element in Eddington-Finkelstein coordinates:

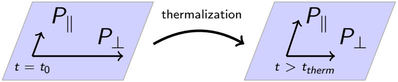
$$ds^2 = 2drdt - A(r,t)dt^2 + \Sigma(r,t)^2\left(e^{-2B(r,t)}dx_{\parallel}^2 + \underbrace{e^{B(r,t)}d\vec{x}_{\perp}^2}_{O(2)}\right)$$

Chesler-Yaffe method

# Thermalization of $\mathcal{N} = 4$ SYM Plasma

Energy momentum tensor (EMT) of the anisotropic SYM-plasma:

$$T_{\mu\nu} \propto \mathrm{diag}\left[\epsilon, P_{\|}(t), \underbrace{P_{\perp}(t), P_{\perp}(t)}_{O(2)}\right]$$




AdS/CFT relates $T_{\mu\nu}$ to the metric of an anisotropic AdS-BH.

Line element in Eddington-Finkelstein coordinates:

$$ds^2 = 2drdt - A(r,t)dt^2 + \Sigma(r,t)^2\left(e^{-2B(r,t)}dx_{\|}^2 + \underbrace{e^{B(r,t)}d\vec{x}_{\perp}^2}_{O(2)}\right)$$

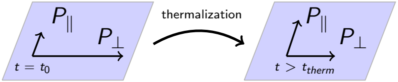
Chesler-Yaffe method

- In characteristic formulation (null-slicing) the Einstein eq. decouple to a nested system of linear ODEs.

# Thermalization of $\mathcal{N} = 4$ SYM Plasma

Energy momentum tensor (EMT) of the anisotropic SYM-plasma:

$$T_{\mu\nu} \propto \mathrm{diag}\left[\epsilon, P_\parallel(t), \underbrace{P_\perp(t), P_\perp(t)}_{O(2)}\right]$$




AdS/CFT relates $T_{\mu\nu}$ to the metric of an anisotropic AdS-BH.

Line element in Eddington-Finkelstein coordinates:

$$ds^2 = 2drdt - A(r,t)dt^2 + \Sigma(r,t)^2\left(e^{-2B(r,t)}dx_\parallel^2 + \underbrace{e^{B(r,t)}d\vec{x}_\perp^2}_{O(2)}\right)$$

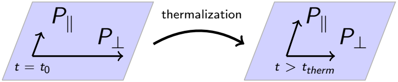
Chesler-Yaffe method

- In characteristic formulation (null-slicing) the Einstein eq. decouple to a nested system of linear ODEs.
- Use spectral method to solve BVP on each null-slice.

# Thermalization of $\mathcal{N} = 4$ SYM Plasma

Energy momentum tensor (EMT) of the anisotropic SYM-plasma:

$$T_{\mu\nu} \propto \mathrm{diag}\big[\epsilon, P_{\|}(t), \underbrace{P_{\perp}(t), P_{\perp}(t)}_{O(2)}\big]$$




AdS/CFT relates $T_{\mu\nu}$ to the metric of an anisotropic AdS-BH.

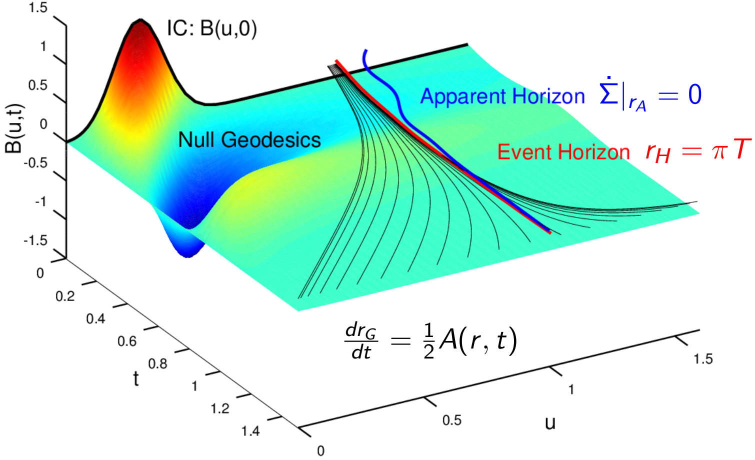
Line element in Eddington-Finkelstein coordinates:

$$ds^2 = 2drdt - A(r,t)dt^2 + \Sigma(r,t)^2\big(e^{-2B(r,t)}dx_{\|}^2 + \underbrace{e^{B(r,t)}d\vec{x}_{\perp}^2}_{O(2)}\big)$$

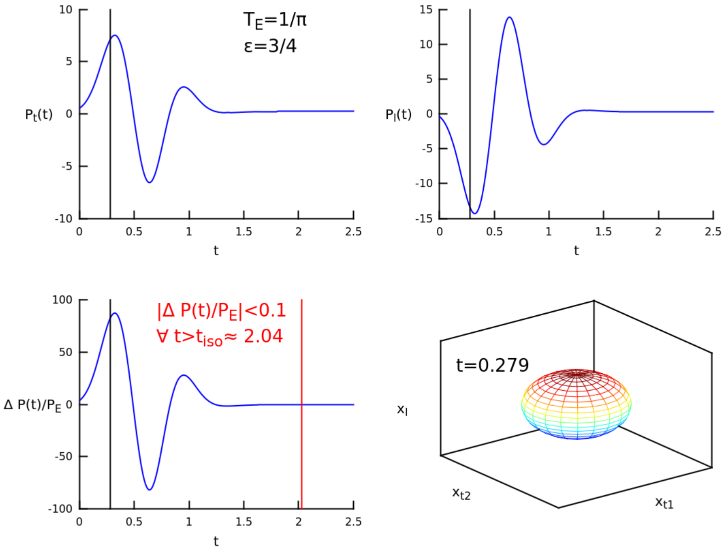
Chesler-Yaffe method

- In characteristic formulation (null-slicing) the Einstein eq. decouple to a nested system of linear ODEs.
- Use spectral method to solve BVP on each null-slice.
- Evolve with Runge-Kutta method between null-slices.

# Numerical Solution: Anisotropy Function B(u,t)



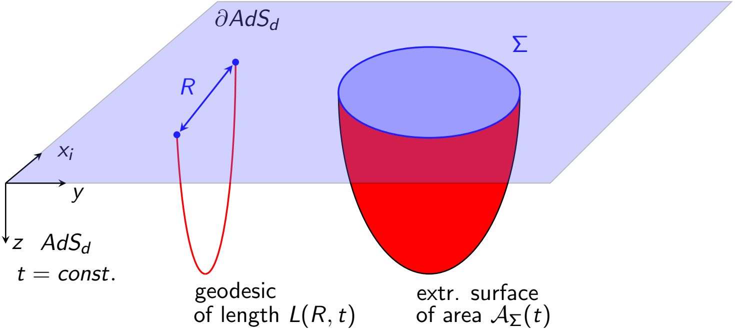
# EMT of the anisotropic $\mathcal{N} = 4$ SYM plasma



# Two-Point Functions and Entanglement Entropy

Various non-local observables in the boundary theory have holographic prescriptions in terms of extremal surfaces:

- Two-point functions: $G(R,t) \propto e^{-mL(R,t)}$
- Entanglement entropy: $S_\Sigma = \frac{\mathcal{A}_\Sigma(t)}{4G_N}$



# Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

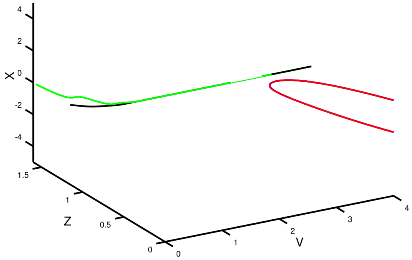
Geodesic equation as two-point boundary value problem (2PBVP):

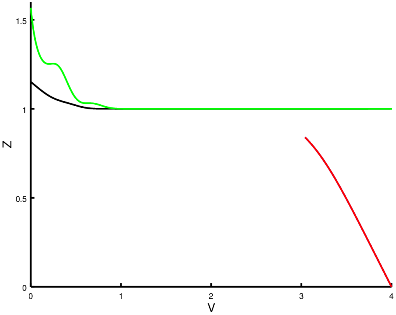
$$\ddot{X}^{\mu}(\tau) + \Gamma^{\mu}_{\alpha\beta}\dot{X}^{\alpha}(\tau)\dot{X}^{\beta}(\tau) = 0, \quad BCs : X^{\mu}(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix}$$

# Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

Geodesic equation as two-point boundary value problem (2PBVP):

$$\ddot{X}^\mu(\tau) + \Gamma^\mu_{\alpha\beta}\dot{X}^\alpha(\tau)\dot{X}^\beta(\tau) = 0, \quad BCs: X^\mu(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix}$$

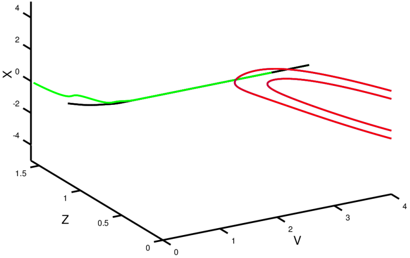


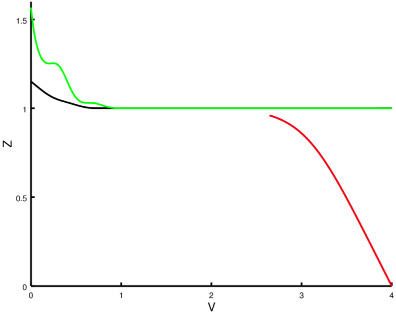



# Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

Geodesic equation as two-point boundary value problem (2PBVP):

$$\ddot{X}^\mu(\tau) + \Gamma^\mu_{\alpha\beta}\dot{X}^\alpha(\tau)\dot{X}^\beta(\tau) = 0, \quad BCs : X^\mu(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix}$$

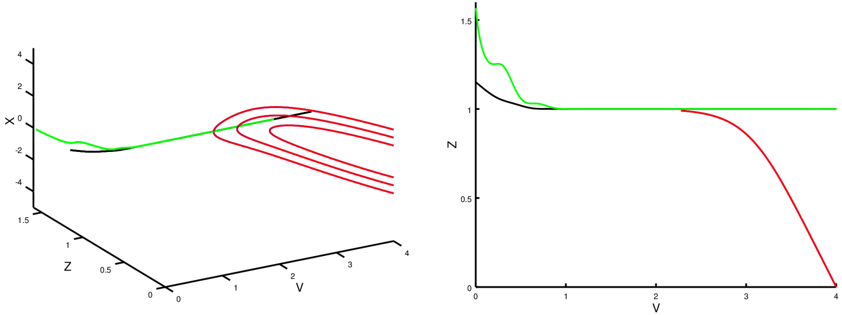


# Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

Geodesic equation as two-point boundary value problem (2PBVP):

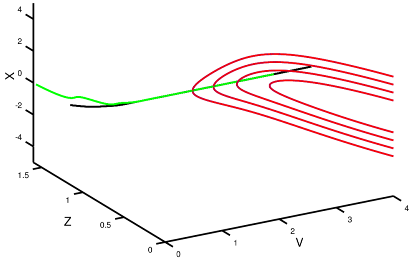
$$\ddot{X}^{\mu}(\tau) + \Gamma^{\mu}_{\alpha\beta}\dot{X}^{\alpha}(\tau)\dot{X}^{\beta}(\tau) = 0, \quad BCs : X^{\mu}(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix}$$

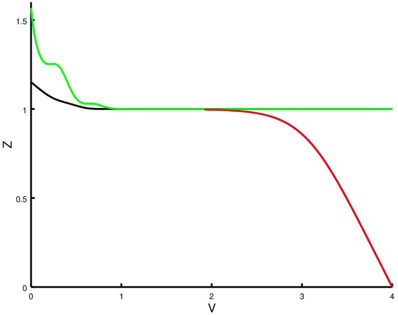


# Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

Geodesic equation as two-point boundary value problem (2PBVP):

$$\ddot{X}^\mu(\tau) + \Gamma^\mu_{\alpha\beta}\dot{X}^\alpha(\tau)\dot{X}^\beta(\tau) = 0, \quad BCs : X^\mu(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix}$$

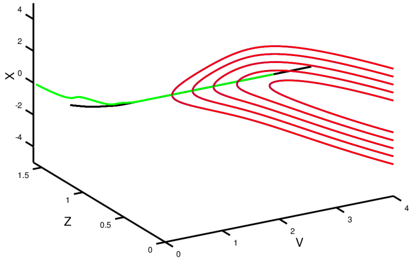


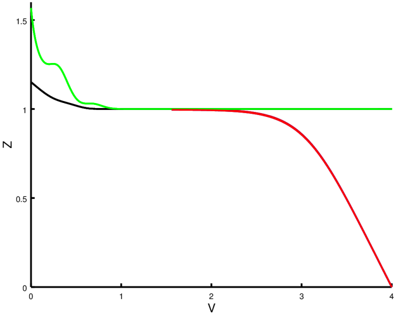



# Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

Geodesic equation as two-point boundary value problem (2PBVP):

$$\ddot{X}^\mu(\tau) + \Gamma^\mu_{\alpha\beta}\dot{X}^\alpha(\tau)\dot{X}^\beta(\tau) = 0, \quad BCs : X^\mu(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix}$$

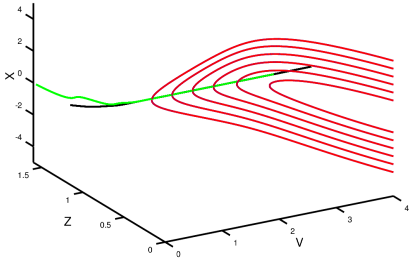


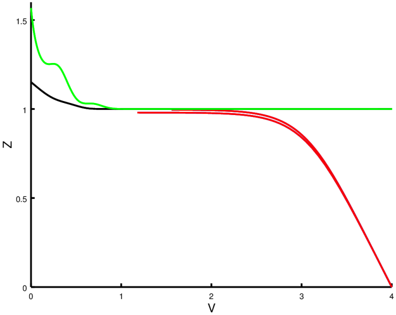



# Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

Geodesic equation as two-point boundary value problem (2PBVP):

$$\ddot{X}^\mu(\tau) + \Gamma^\mu_{\alpha\beta}\dot{X}^\alpha(\tau)\dot{X}^\beta(\tau) = 0, \quad BCs : X^\mu(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix}$$

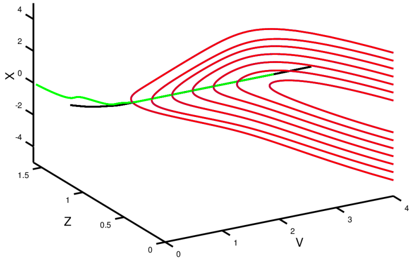


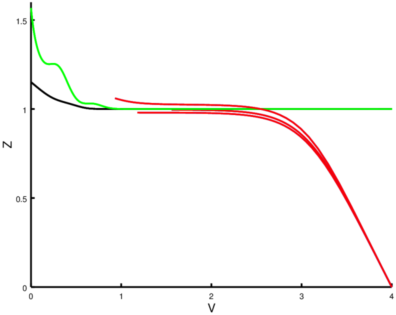



# Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

Geodesic equation as two-point boundary value problem (2PBVP):

$$\ddot{X}^\mu(\tau) + \Gamma^\mu_{\alpha\beta}\dot{X}^\alpha(\tau)\dot{X}^\beta(\tau) = 0, \quad BCs : X^\mu(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix}$$

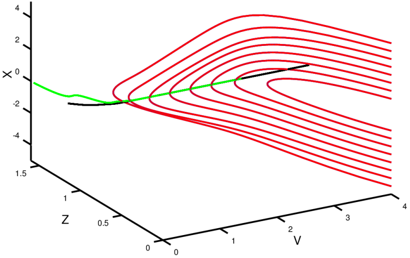


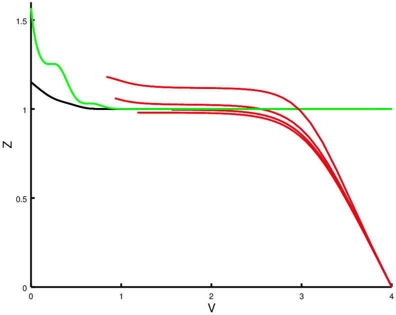



# Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

Geodesic equation as two-point boundary value problem (2PBVP):

$$\ddot{X}^\mu(\tau) + \Gamma^\mu_{\alpha\beta}\dot{X}^\alpha(\tau)\dot{X}^\beta(\tau) = 0, \quad BCs : X^\mu(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix}$$

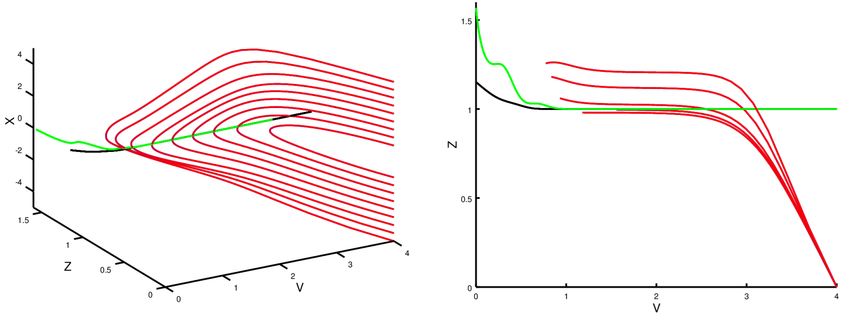


# Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

Geodesic equation as two-point boundary value problem (2PBVP):

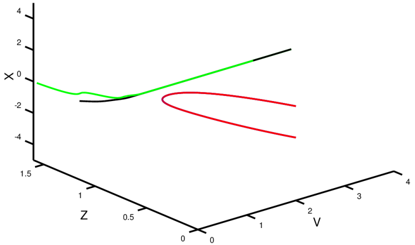
$$\ddot{X}^\mu(\tau) + \Gamma^\mu_{\alpha\beta}\dot{X}^\alpha(\tau)\dot{X}^\beta(\tau) = 0, \quad BCs : X^\mu(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix}$$

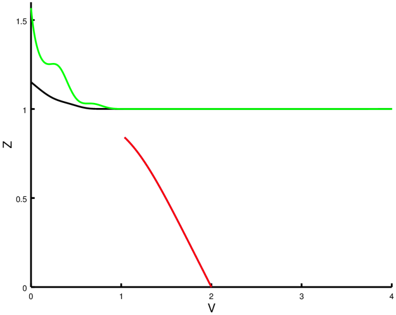


# Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

Geodesic equation as two-point boundary value problem (2PBVP):

$$\ddot{X}^\mu(\tau) + \Gamma^\mu_{\alpha\beta}\dot{X}^\alpha(\tau)\dot{X}^\beta(\tau) = 0, \quad BCs : X^\mu(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix}$$

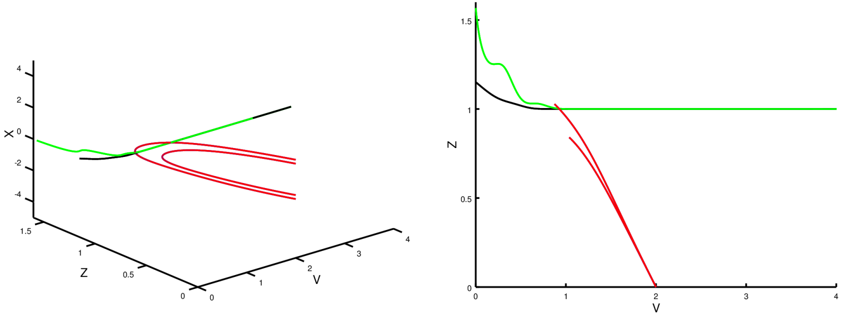


# Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

Geodesic equation as two-point boundary value problem (2PBVP):

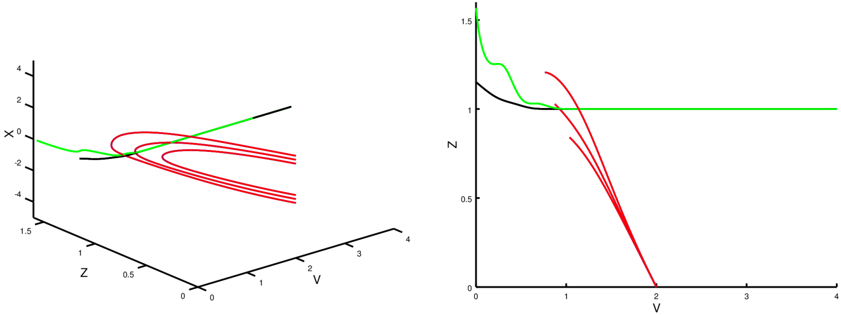
$$\ddot{X}^{\mu}(\tau) + \Gamma^{\mu}_{\alpha\beta}\dot{X}^{\alpha}(\tau)\dot{X}^{\beta}(\tau) = 0, \quad BCs : X^{\mu}(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix}$$



# Spacelike geodesics anchored to the boundary of the anisotropic $AdS_5$ geometry

Geodesic equation as two-point boundary value problem (2PBVP):

$$\ddot{X}^\mu(\tau) + \Gamma^\mu_{\alpha\beta}\dot{X}^\alpha(\tau)\dot{X}^\beta(\tau) = 0, \quad BCs: X^\mu(\pm 1) = \begin{pmatrix} V(\pm 1) \\ Z(\pm 1) \\ X(\pm 1) \end{pmatrix} = \begin{pmatrix} t_0 \\ 0 \\ \pm L/2 \end{pmatrix}$$



# Conclusion & Outlook

## Conclusion

- Black hole physics (GR) can be used to study non-equilibrium dynamics of strongly coupled gauge theories (QFT).
- Within AdS/CFT various non-local observables can be computed from geodesics and extremal surfaces.
- In time dependent backgrounds there is information from behind the black hole horizon encoded in the two point functions.

## Outlook

- Next we want to study entanglement entropy using extremal surfaces.
- "Numerical holography" is a rather young discipline - there is still much to discover!

# Conclusion & Outlook

## Conclusion

- Black hole physics (GR) can be used to study non-equilibrium dynamics of strongly coupled gauge theories (QFT).
- Within AdS/CFT various non-local observables can be computed from geodesics and extremal surfaces.
- In time dependent backgrounds there is information from behind the black hole horizon encoded in the two point functions.

## Outlook

- Next we want to study entanglement entropy using extremal surfaces.
- "Numerical holography" is a rather young discipline - there is still much to discover!

# Conclusion & Outlook

## Conclusion

- Black hole physics (GR) can be used to study non-equilibrium dynamics of strongly coupled gauge theories (QFT).
- Within AdS/CFT various non-local observables can be computed from geodesics and extremal surfaces.
- In time dependent backgrounds there is information from behind the black hole horizon encoded in the two point functions.

## Outlook

- Next we want to study entanglement entropy using extremal surfaces.
- "Numerical holography" is a rather young discipline - there is still much to discover!

# Conclusion & Outlook

**Conclusion**

- Black hole physics (GR) can be used to study non-equilibrium dynamics of strongly coupled gauge theories (QFT).
- Within AdS/CFT various non-local observables can be computed from geodesics and extremal surfaces.
- In time dependent backgrounds there is information from behind the black hole horizon encoded in the two point functions.

**Outlook**

- Next we want to study entanglement entropy using extremal surfaces.
- "Numerical holography" is a rather young discipline - there is still much to discover!

# Conclusion & Outlook

**Conclusion**

- Black hole physics (GR) can be used to study non-equilibrium dynamics of strongly coupled gauge theories (QFT).
- Within AdS/CFT various non-local observables can be computed from geodesics and extremal surfaces.
- In time dependent backgrounds there is information from behind the black hole horizon encoded in the two point functions.

**Outlook**

- Next we want to study entanglement entropy using extremal surfaces.
- "Numerical holography" is a rather young discipline - there is still much to discover!