Chaotic Quarks in Holographic QCD

Avik Banerjee
SINP , HBNI

The Myriad Colorful Ways of Understanding Extreme QCD Matter

ICTS , Bengaluru

Based on

Earlier Works

1. *A Bound on Chaos* (Maldacena , Shenker, Stanford)
2. *Stringy Effects in Scrambling* (Shenker, Stanford)
3. *Chaotic Strings in AdS/CFT* (Jan de Boer , E. Llabres, Juan Pedraza, D. Vegh)

Our Works

arXiv:1811.04977, arXiv:1809.02090 (AB , A. Kundu, R.Poojary)

Introduction and Motivation

Introduction and Motivation

Chaos is a very natural phenomenon. Thermal systems with large d.o.f are generically chaotic .

Introduction and Motivation

Chaos is a very natural phenomenon. Thermal systems with large d.o.f are generically chaotic .

Study of chaos in quantum systems is in general difficult,

Introduction and Motivation

Chaos is a very natural phenomenon. Thermal systems with large d.o.f are generically chaotic .

Study of chaos in quantum systems is in general difficult, and more so when the system is strongly coupled.

Introduction and Motivation

Chaos is a very natural phenomenon. Thermal systems with large d.o.f are generically chaotic .

Study of chaos in quantum systems is in general difficult, and more so when the system is strongly coupled. Holography provides a unique nonperturbative framework to address such difficult yet interesting questions in strongly coupled theories.

Introduction and Motivation

Chaos is a very natural phenomenon. Thermal systems with large d.o.f are generically chaotic .

Study of chaos in quantum systems is in general difficult, and more so when the system is strongly coupled. Holography provides a unique nonperturbative framework to address such difficult yet interesting questions in strongly coupled theories.

Holography provides a sharp upper bound on the rate of growth of chaos in the strongly coupled theories(gluonic sector).

Introduction and Motivation

Chaos is a very natural phenomenon. Thermal systems with large d.o.f are generically chaotic .

Study of chaos in quantum systems is in general difficult, and more so when the system is strongly coupled. Holography provides a unique nonperturbative framework to address such difficult yet interesting questions in strongly coupled theories.

Holography provides a sharp upper bound on the rate of growth of chaos in the strongly coupled theories(gluonic sector). How does this bound translate to the flavor sector.

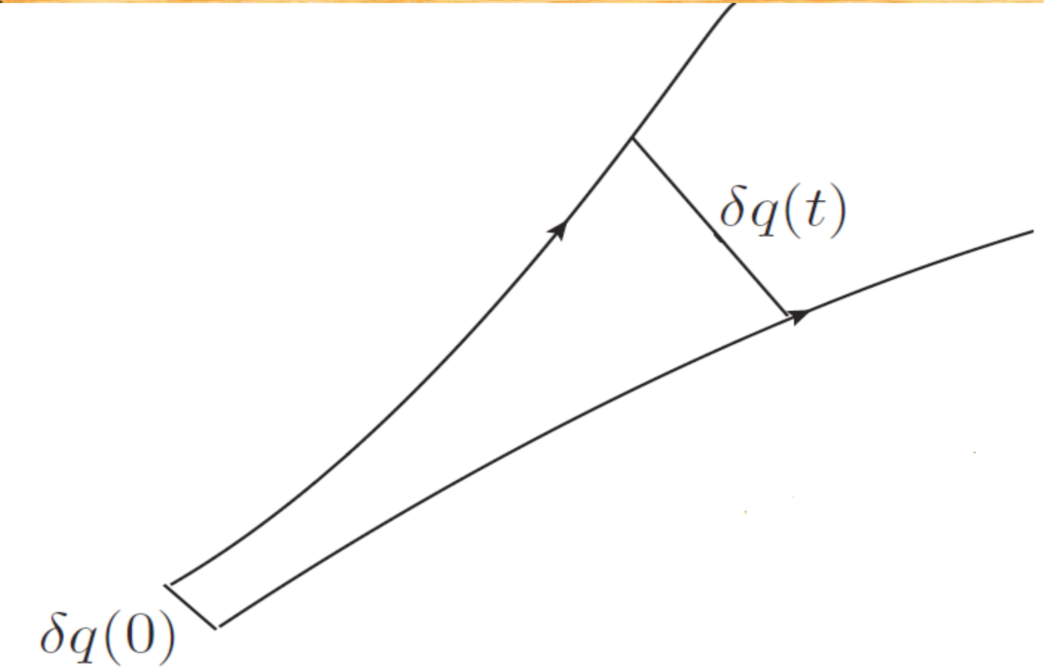
Outline

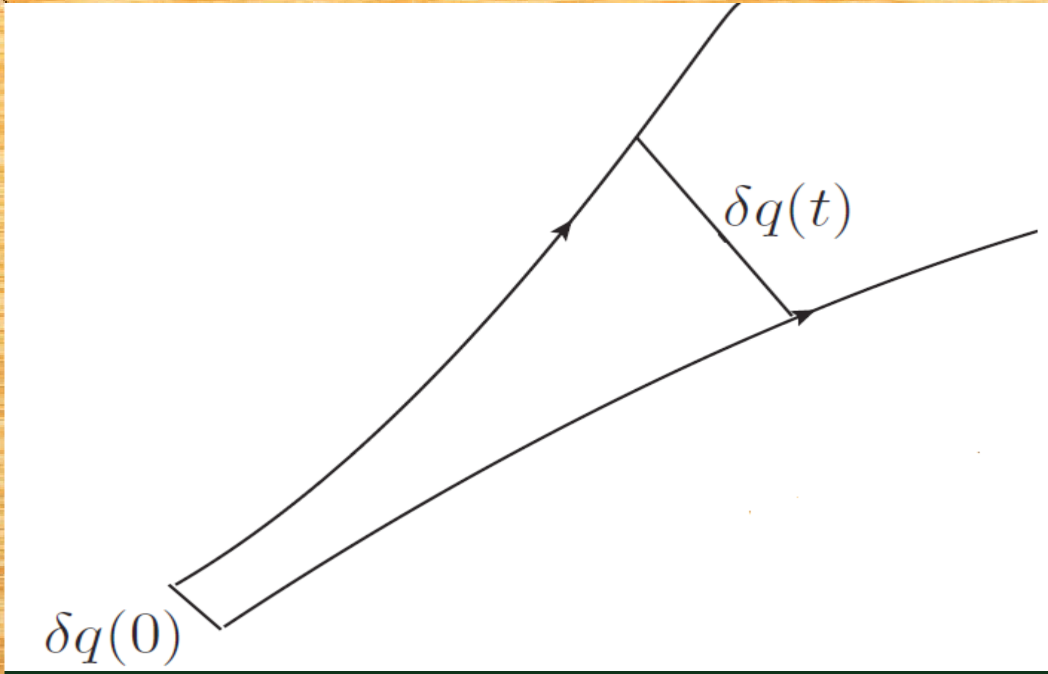
1. Chaos in Quantum Systems – Basic Idea

2. The Holographic Approach

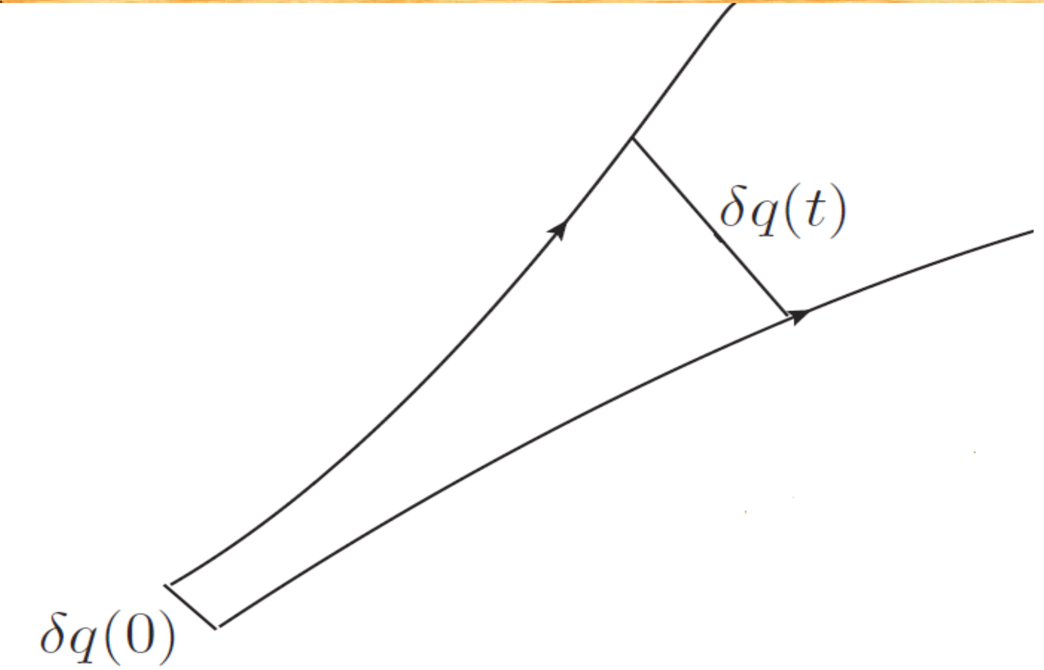
3. Chaos in Flavor Sector

4. Concluding Remarks and Open Questions


$\delta q(t)$
$\delta q(0)$

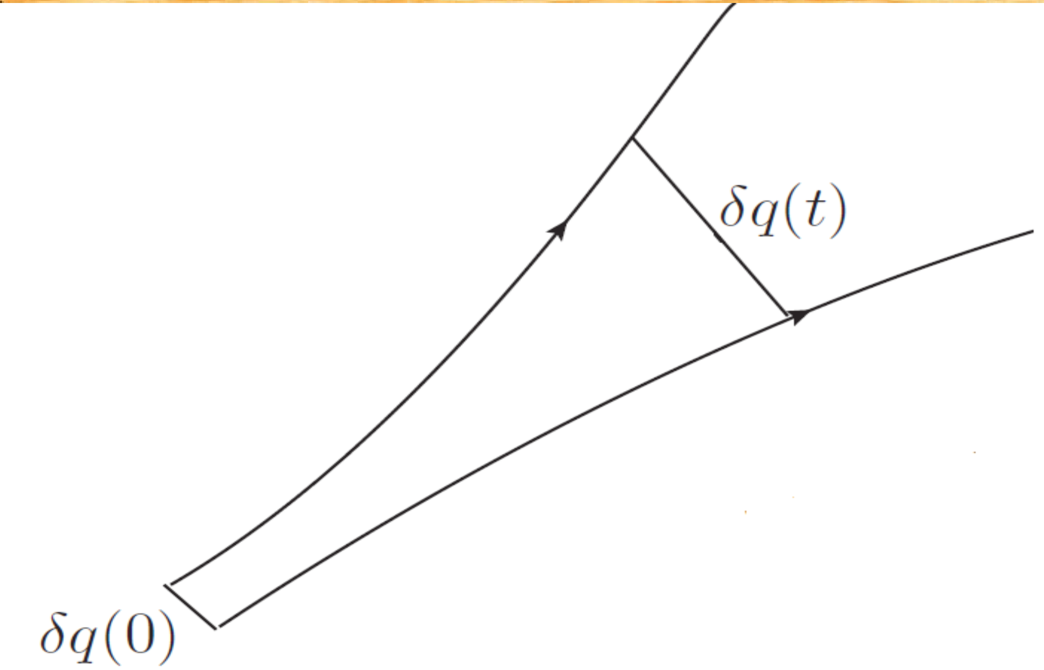


$$\frac{\delta q(t)}{\delta q(0)} = e^{\lambda_L t}$$



$$\frac{\delta q(t)}{\delta q(0)} = e^{\lambda_L t}$$

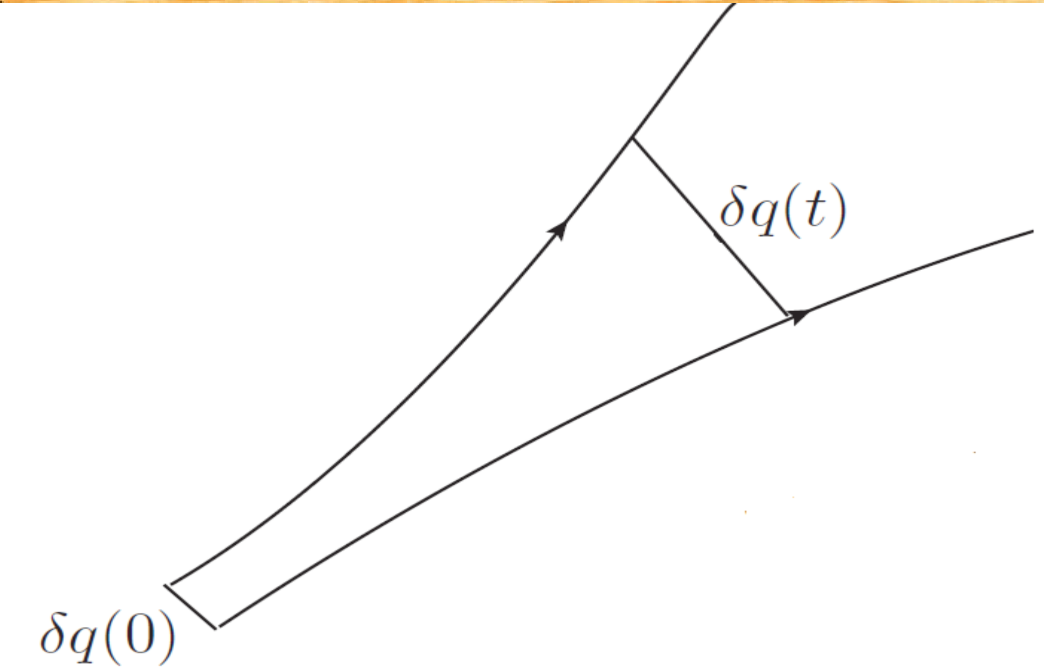
$$\boxed{\lambda_L \leq 2\pi T}$$



$$\frac{\delta q(t)}{\delta q(0)} = e^{\lambda_L t}$$

$$\lambda_L \leq 2\pi T$$

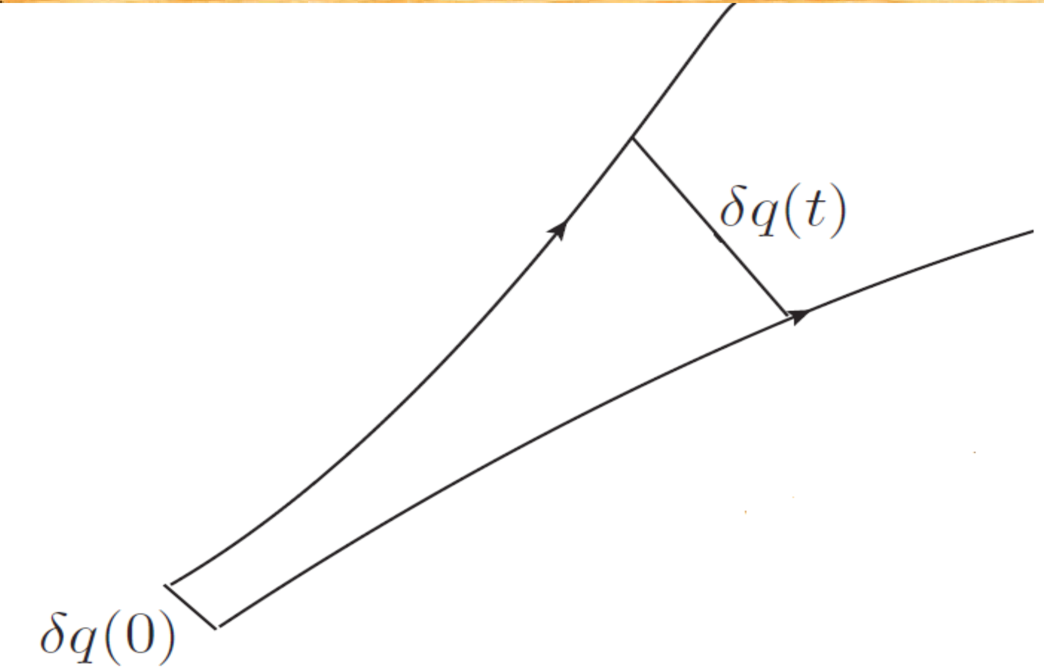
$$\{q(t), p(0)\}$$



$$\frac{\delta q(t)}{\delta q(0)} = e^{\lambda_L t}$$

$$\lambda_L \leq 2\pi T$$

$$\{q(t), p(0)\} \rightarrow \frac{1}{i\hbar}[q(t), p(0)]$$

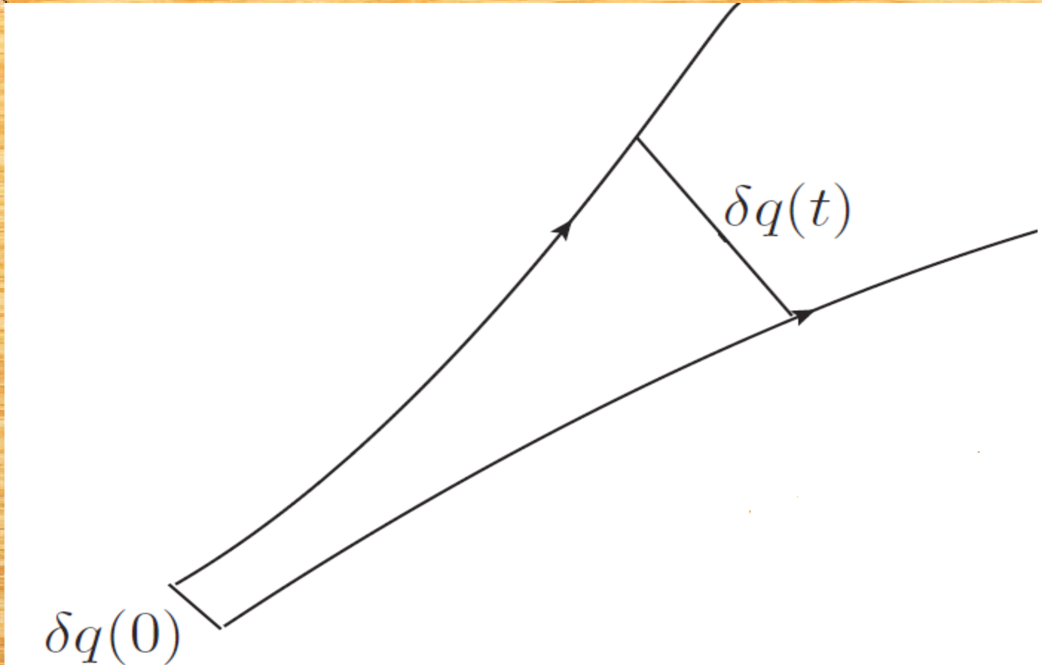


$$\frac{\delta q(t)}{\delta q(0)} = e^{\lambda_L t}$$

$$\lambda_L \leq 2\pi T$$

$$\{q(t), p(0)\} \longrightarrow \frac{1}{i\hbar}[q(t), p(0)]$$

$$C(t) = -\left\langle [W(t), V(0)]^2 \right\rangle_\beta$$



$$\frac{\delta q(t)}{\delta q(0)} = e^{\lambda_L t}$$

$$\lambda_L \leq 2\pi T$$

$$\{q(t), p(0)\} \longrightarrow \frac{1}{i\hbar}[q(t), p(0)]$$

$$C(t) = -\left\langle [W(t), V(0)]^2 \right\rangle_\beta$$

$$\langle W(t)\ W(t)\ V(0)\ V(0) \rangle_\beta$$

(TOC)

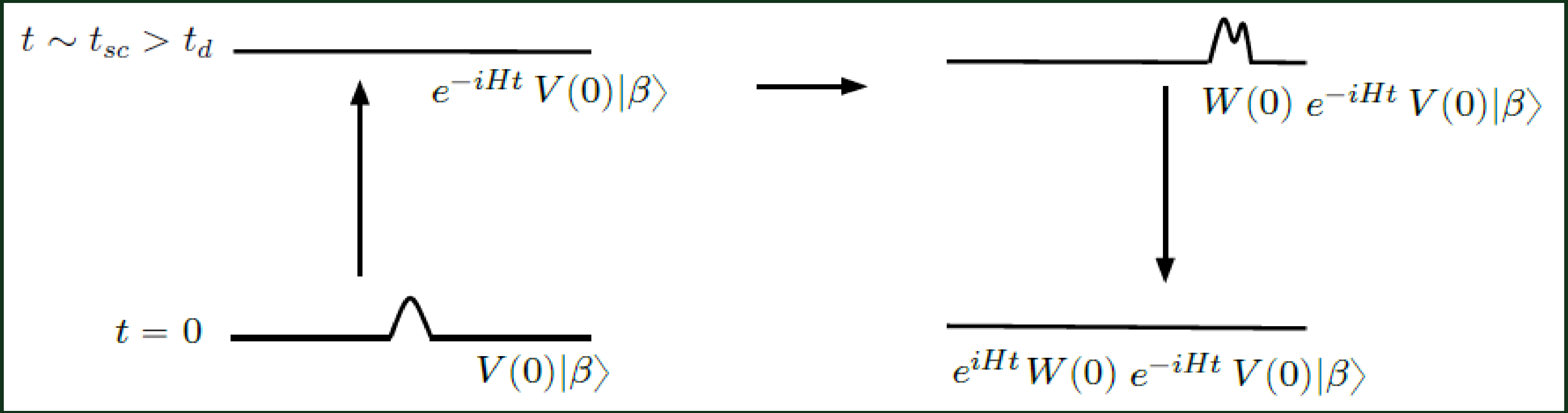
$$\langle W(t)\ V(0)\ W(t)\ V(0) \rangle_\beta$$

(OTOC)

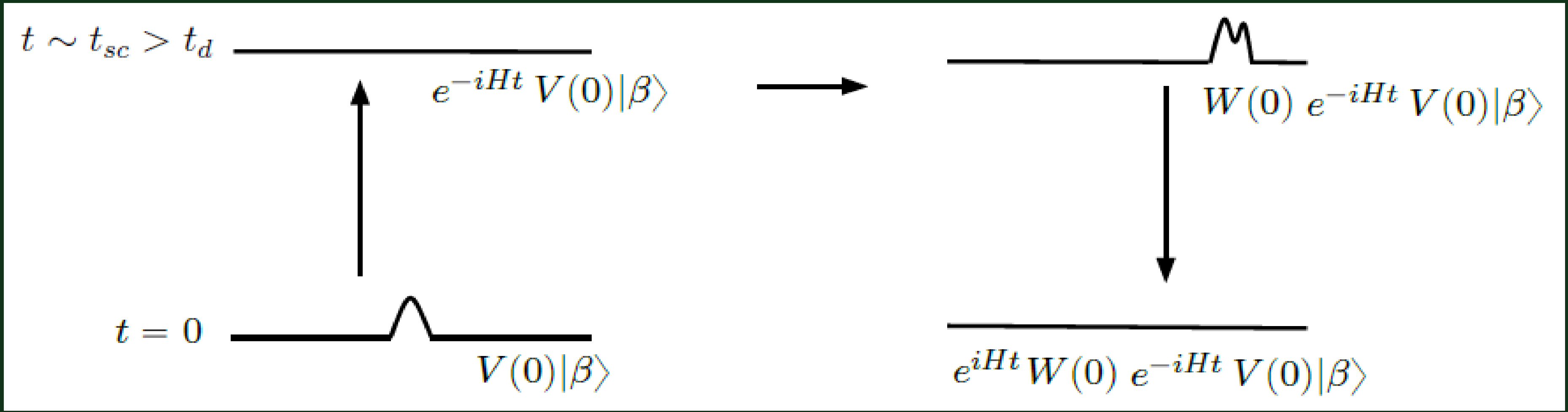
The OTOC can be thought of as overlap of the states $|\psi_1\rangle = W(t)V(0)\ |\beta\rangle$ and $|\psi_2\rangle = V(0)W(t)\ |\beta\rangle$

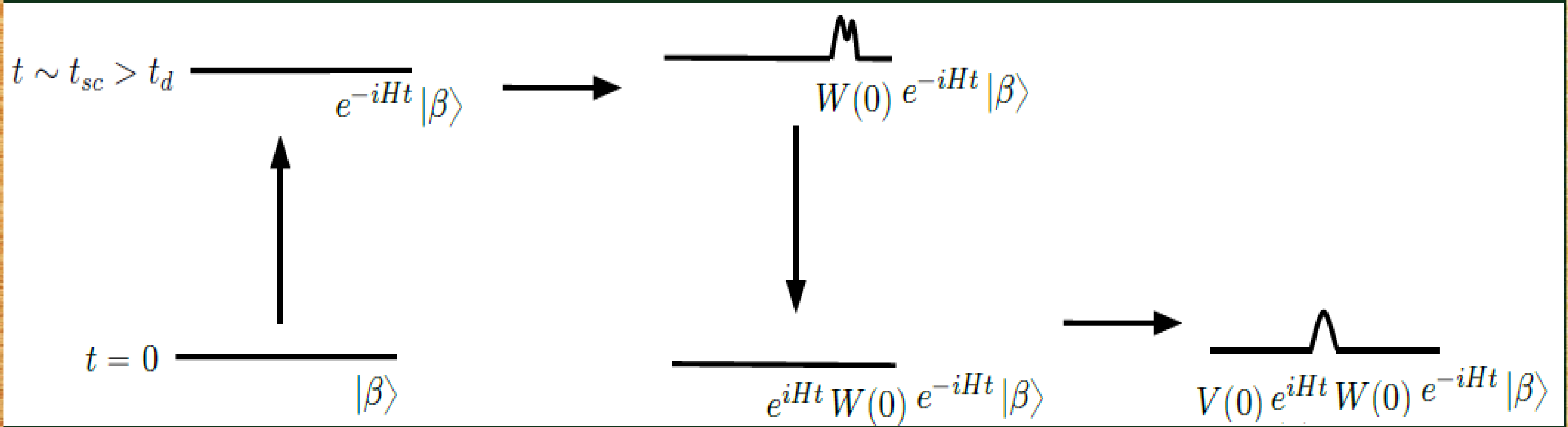
The OTOC can be thought of as overlap of the states $|\psi_1\rangle = W(t)V(0)\ |\beta\rangle$ and $|\psi_2\rangle = V(0)W(t)\ |\beta\rangle \longrightarrow$ becomes small at late times for chaotic systems.

The OTOC can be thought of as overlap of the states $|\psi_1\rangle = W(t)V(0)\ |\beta\rangle$ and $|\psi_2\rangle = V(0)W(t)\ |\beta\rangle \longrightarrow$ becomes small at late times for chaotic systems.

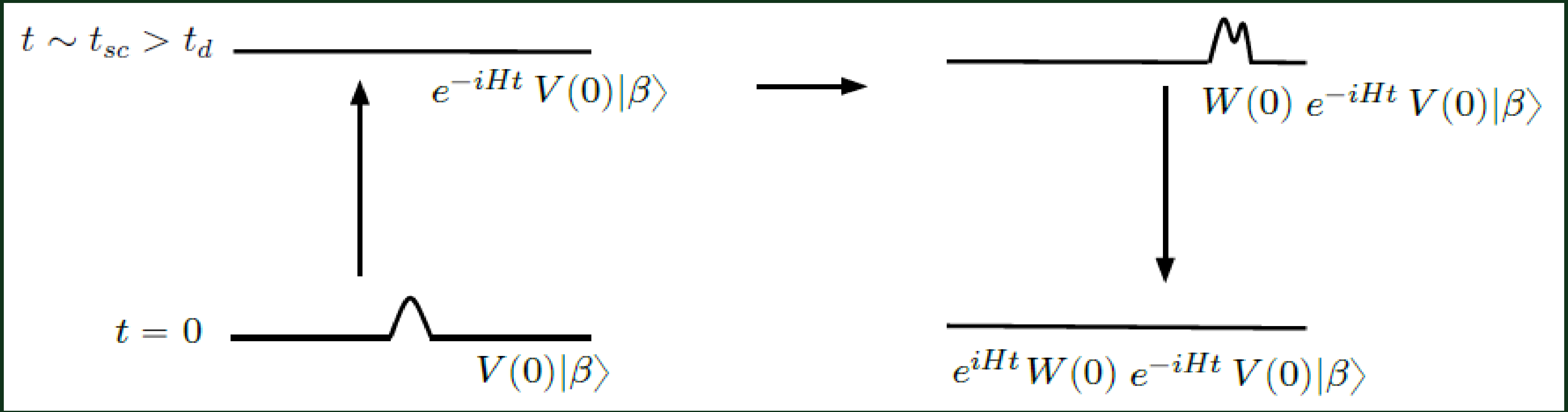


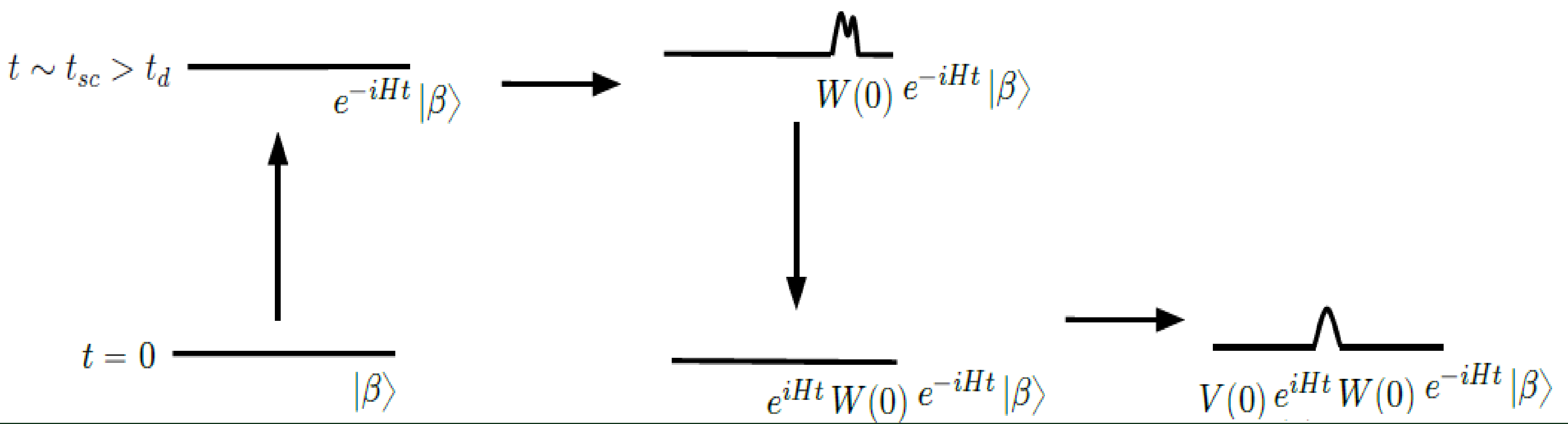
The OTOC can be thought of as overlap of the states $|\psi_1\rangle = W(t)V(0)\ |\beta\rangle$ and $|\psi_2\rangle = V(0)W(t)\ |\beta\rangle \longrightarrow$ becomes small at late times for chaotic systems.





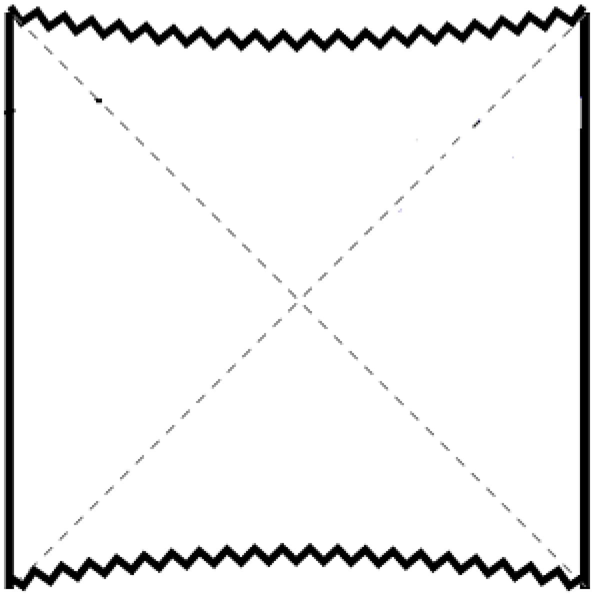
The OTOC can be thought of as overlap of the states $|\psi_1\rangle = W(t)V(0)\ |\beta\rangle$ and $|\psi_2\rangle = V(0)W(t)\ |\beta\rangle \longrightarrow$ becomes small at late times for chaotic systems.



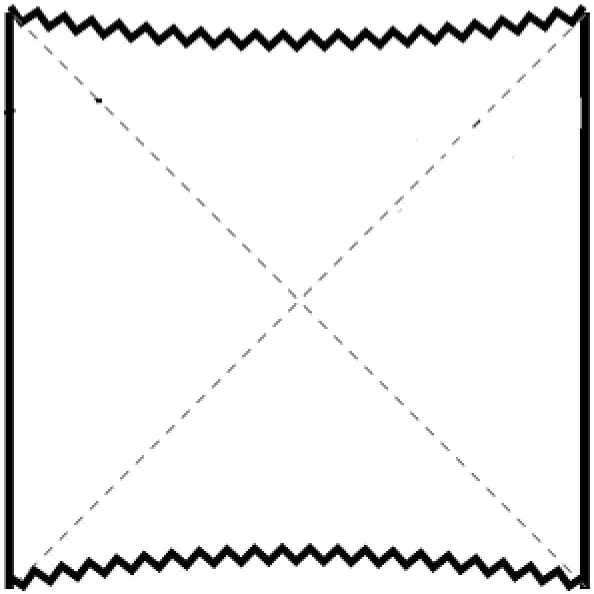


Such OTOCs in QFT are calculated using Schwinger-Keldysh techniques. Alternately, holography gives a simpler and elegant prescription

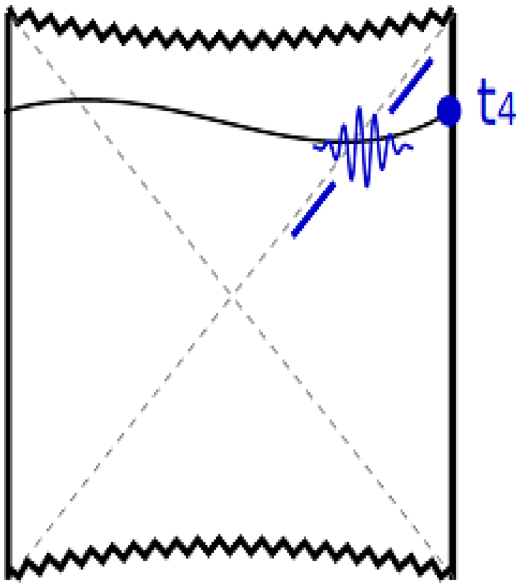
$$|\beta> \quad \equiv$$



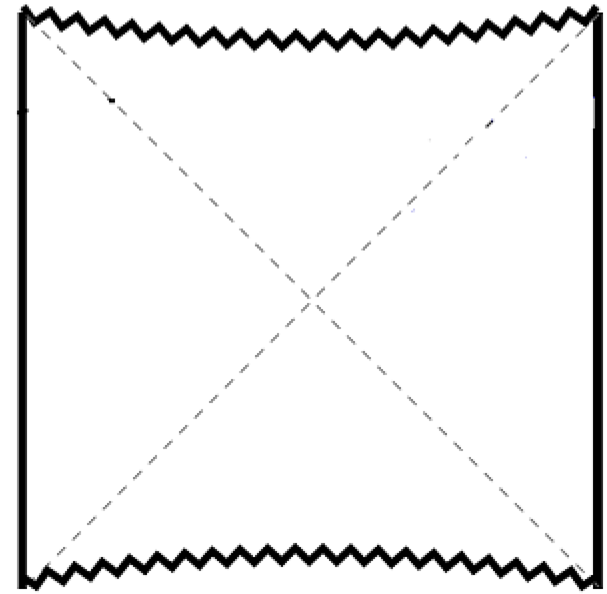
$|\beta>$ $\equiv$



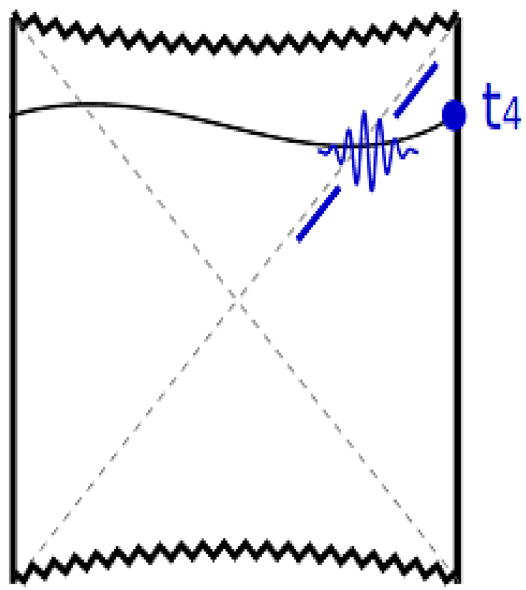
$W(t_4)|\beta>$ $\equiv$

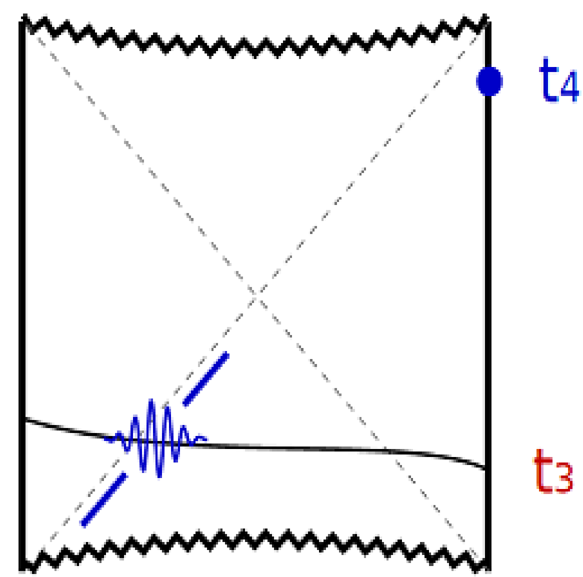


$$|\beta> \quad \equiv$$

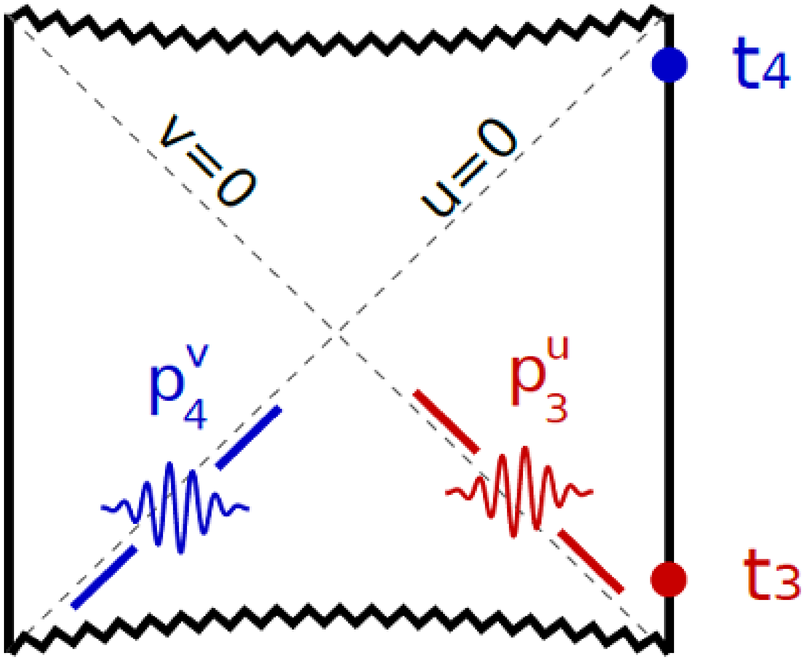


$$W(t_4)|\beta> \quad \equiv$$

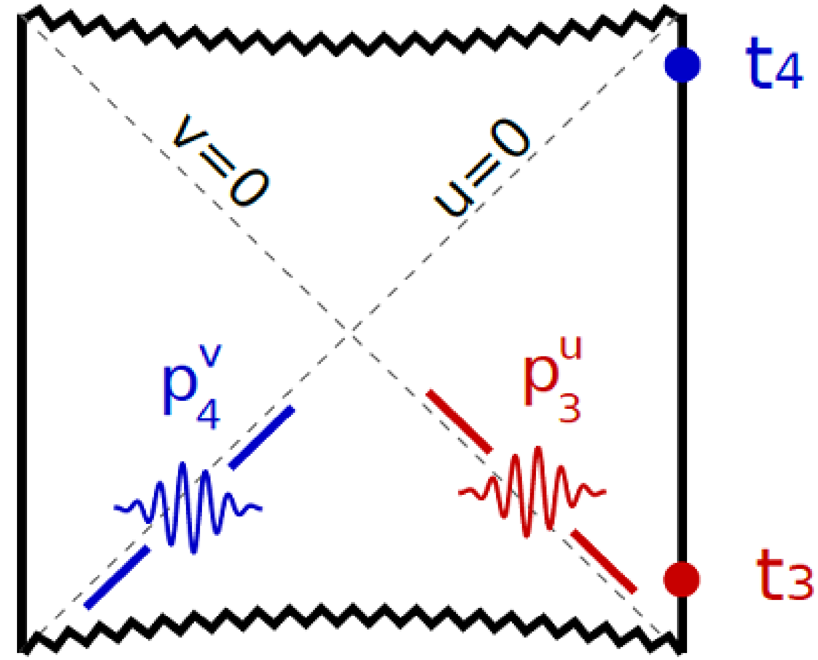




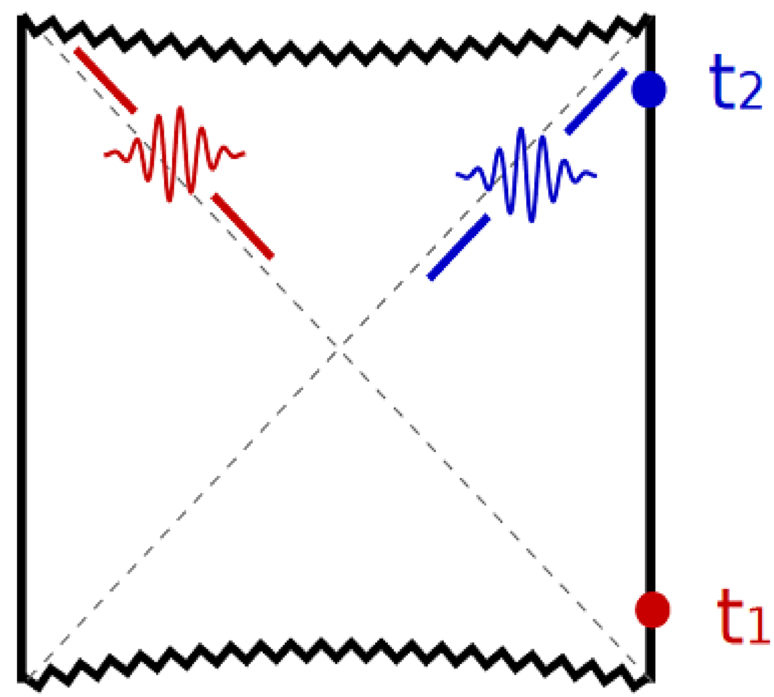
$$V(t_3)W(t_4)|\beta> \quad \equiv$$



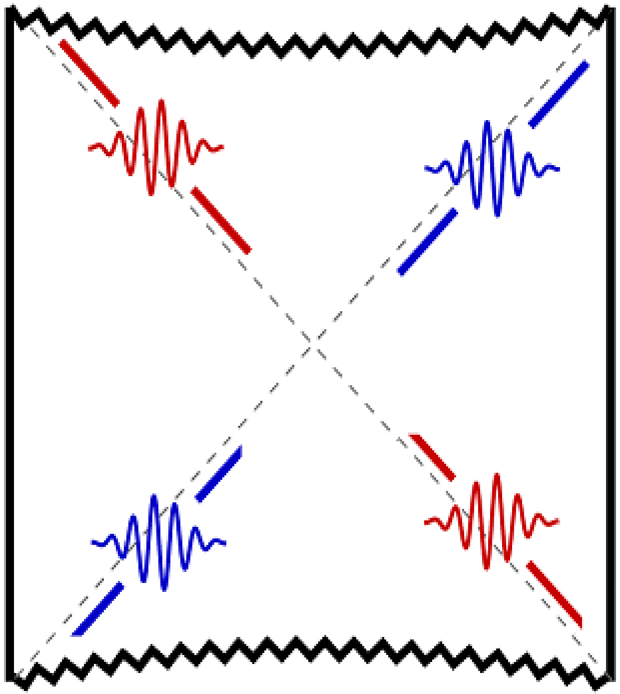
$$V(t_3)W(t_4)|\beta> \quad \equiv$$



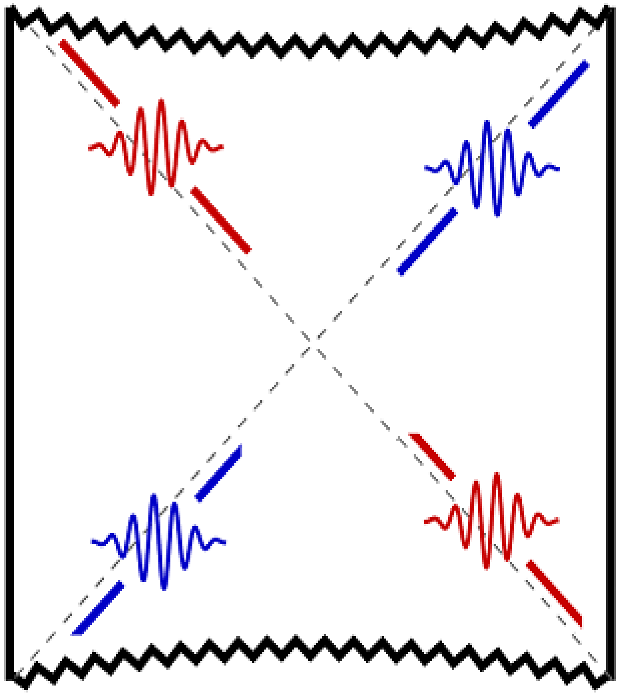
$$W(t_2)V(t_1)\ |\beta> \quad \equiv$$



$$< \beta|V(t_1)W(t_2)\ V(t_3)W(t_4)|\beta > \quad \equiv$$

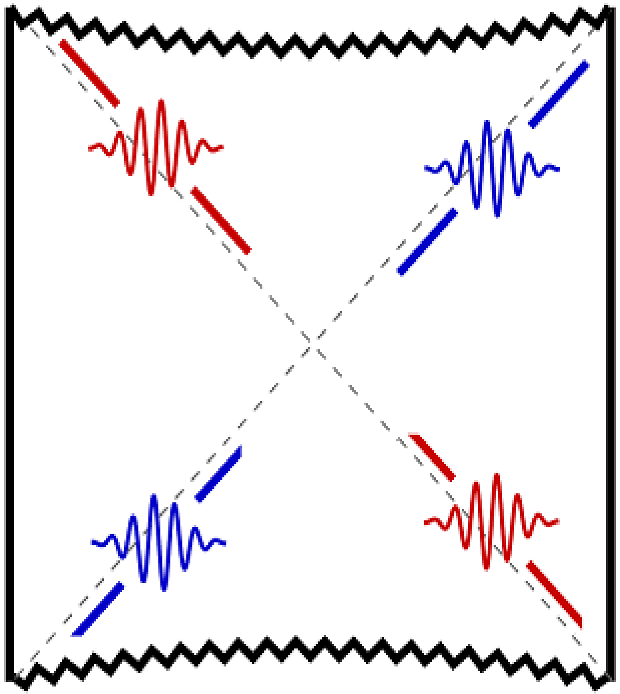


$$< \beta|V(t_1)W(t_2)\ V(t_3)W(t_4)|\beta > \quad \equiv$$



$$= \int dp_1^u dp_2^v \ \ e^{i\delta(s)}\ p_1^u\ p_2^v \ \ \psi_1^*\left(p_1^u\right)\ \ \psi_2^*\left(p_2^v\right)\psi_3\left(p_1^u\right)\psi_4\left(p_2^v\right)$$

$$< \beta|V(t_1)W(t_2)\ V(t_3)W(t_4)|\beta > \ \equiv$$

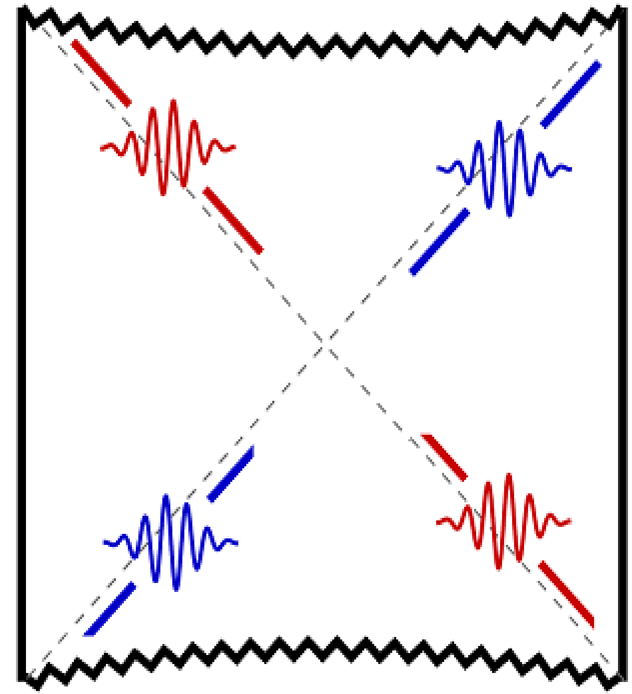


$$= \int dp_1^u dp_2^v \ e^{i\delta(s)}\ p_1^u\ p_2^v \ \psi_1^*\left(p_1^u\right)\ \psi_2^*\left(p_2^v\right)\psi_3\left(p_1^u\right)\psi_4\left(p_2^v\right)$$

$$= 1 - \frac{f_0}{N_c^2}\ e^{\ \frac{2\pi}{\beta}t}$$

Shenker, Stanford

$$< \beta | V(t_1) W(t_2)\ V(t_3) W(t_4) | \beta > \ \equiv$$



$$= \int dp_1^u dp_2^v \ \ e^{i\delta(s)}\ p_1^u\ p_2^v\ \ \psi_1^*\left(p_1^u\right)\ \psi_2^*\left(p_2^v\right) \psi_3\left(p_1^u\right) \psi_4\left(p_2^v\right)$$

$$= 1 - \frac{f_0}{N_c^2}\ e^{\ \frac{2\pi}{\beta} t} \qquad \rightarrow \boxed{t_{sc} \sim \beta\ log N_c^2}$$

Shenker, Stanford

Fluctuations of a thermal plasma with large number of d.o.f exhibit maximal chaos.

Fluctuations of a thermal plasma with large number of d.o.f exhibit maximal chaos.

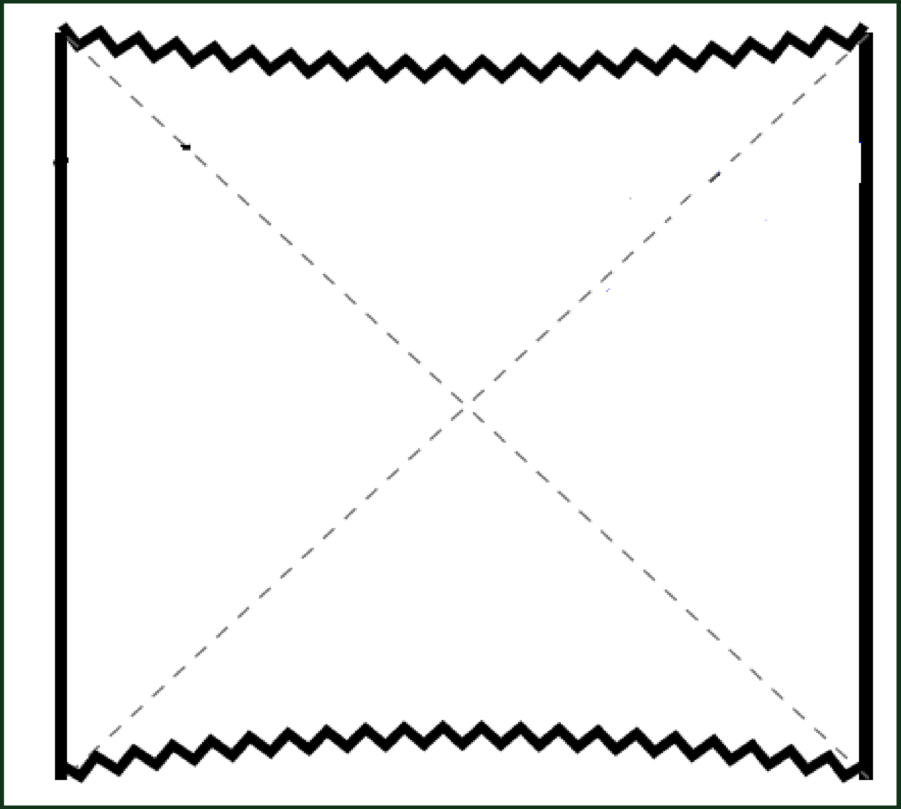
What about the fluctuations of a probe quark added to the thermal plasma.

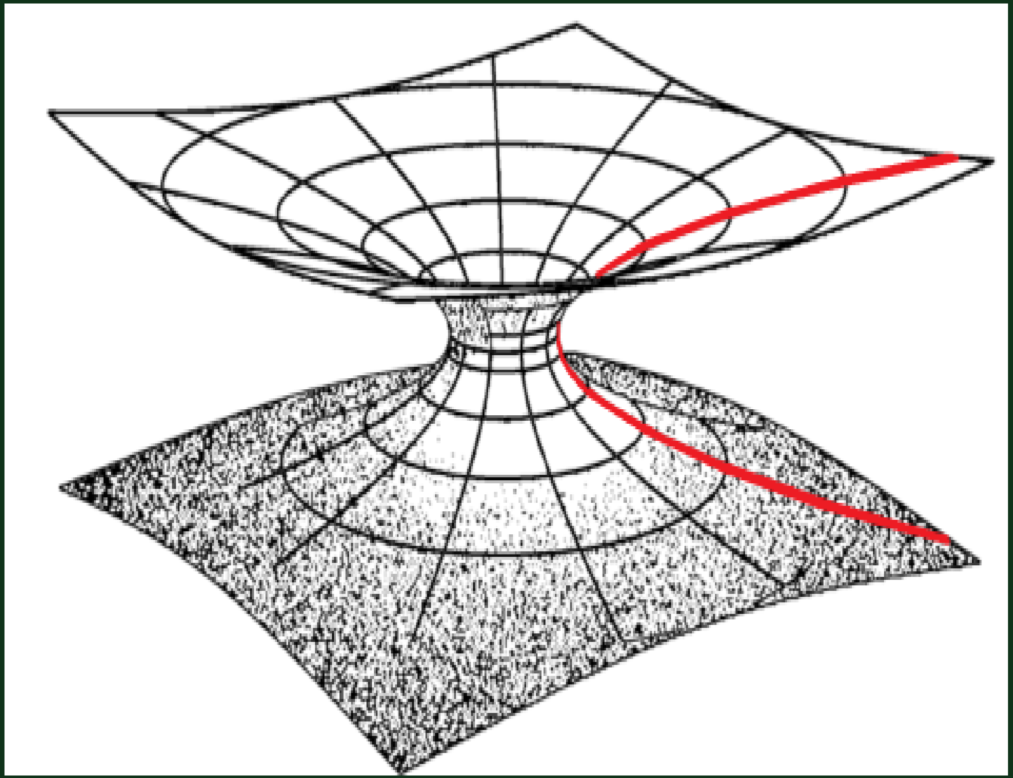
Fluctuations of a thermal plasma with large number of d.o.f exhibit maximal chaos.

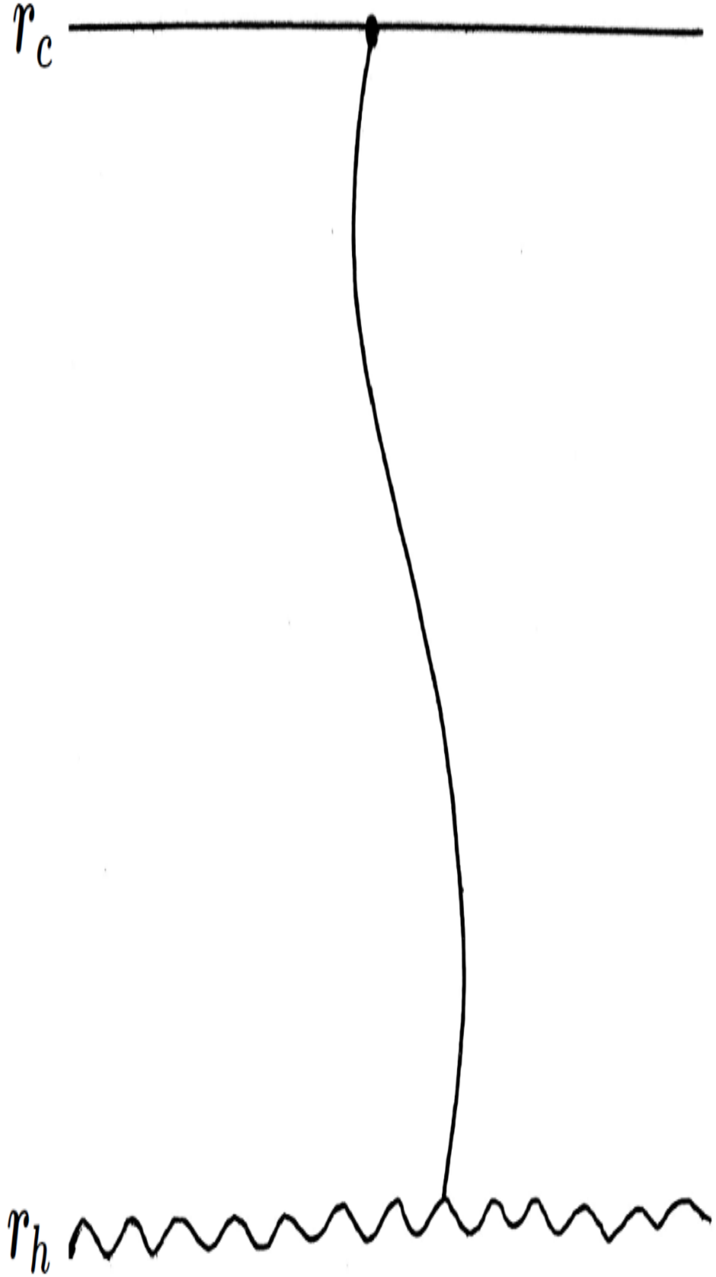
What about the fluctuations of a probe quark added to the thermal plasma. Need to introduce flavors in AdS/CFT -------> Strings and Branes

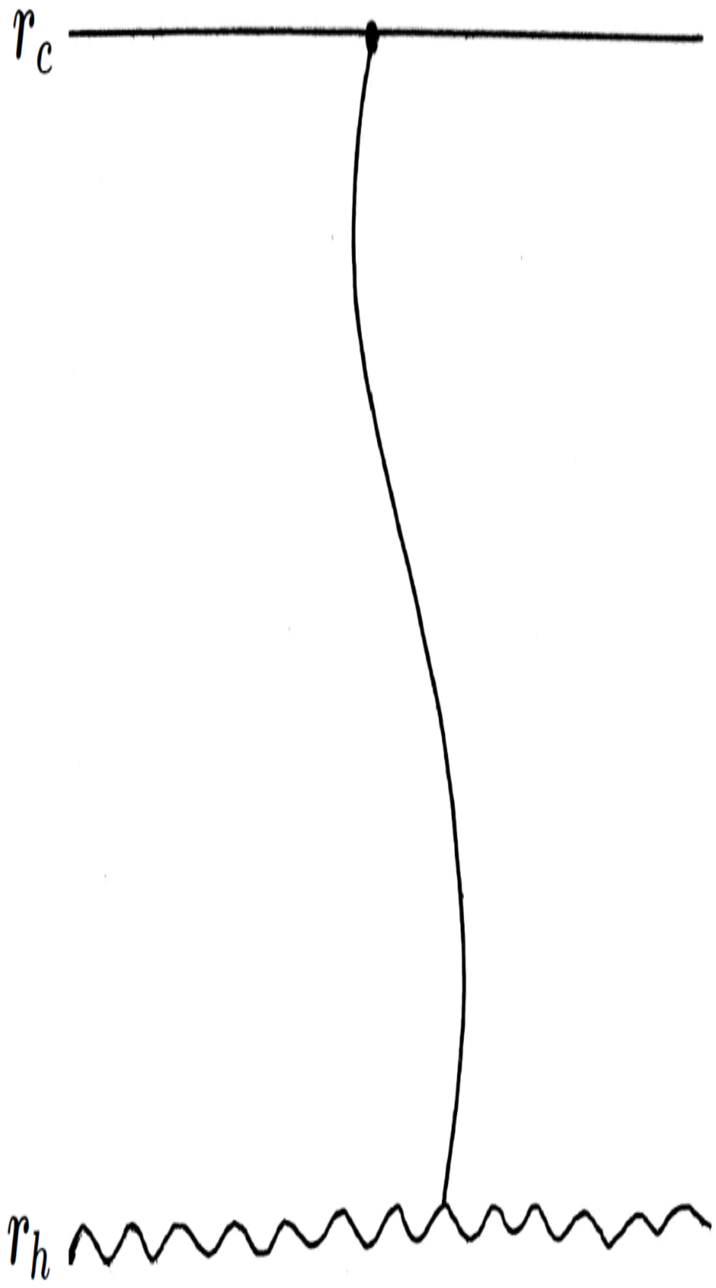
Fluctuations of a thermal plasma with large number of d.o.f exhibit maximal chaos.

What about the fluctuations of a probe quark added to the thermal plasma. Need to introduce flavors in AdS/CFT -------> Strings and Branes



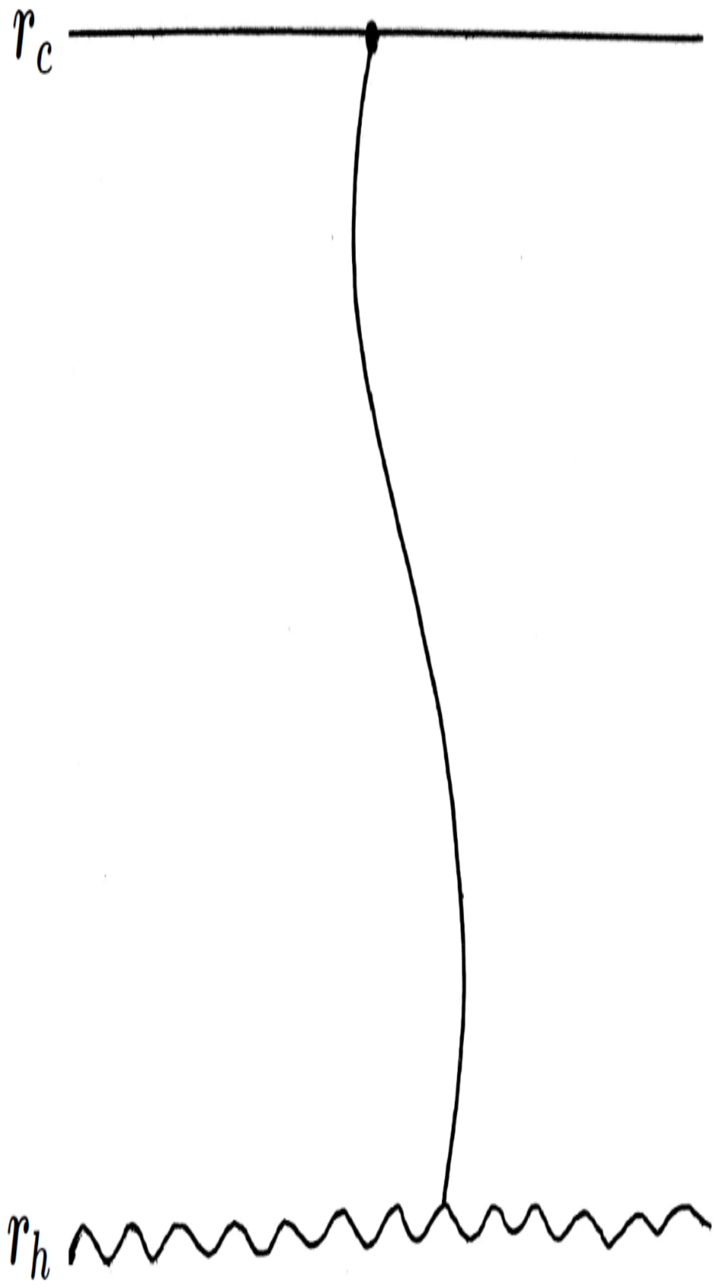



r_c
r_h



String embedded in BTZ background

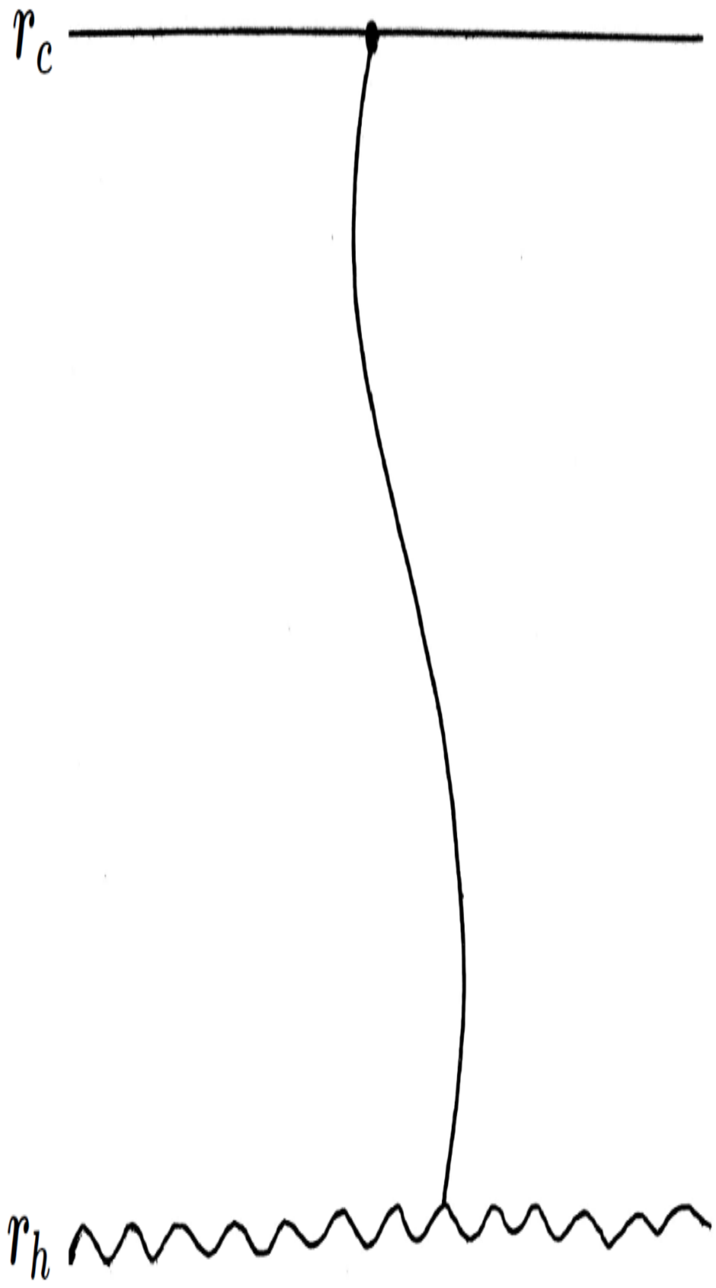
$$ds^2 = -\left(r^2 - r_h^2\right) dt^2 + \frac{dr^2}{\left(r^2 - r_h^2\right)} + r^2 dx^2$$



String embedded in BTZ background

$$ds^2 = -\left(r^2 - r_h^2\right) dt^2 + \frac{dr^2}{\left(r^2 - r_h^2\right)} + r^2 dx^2$$

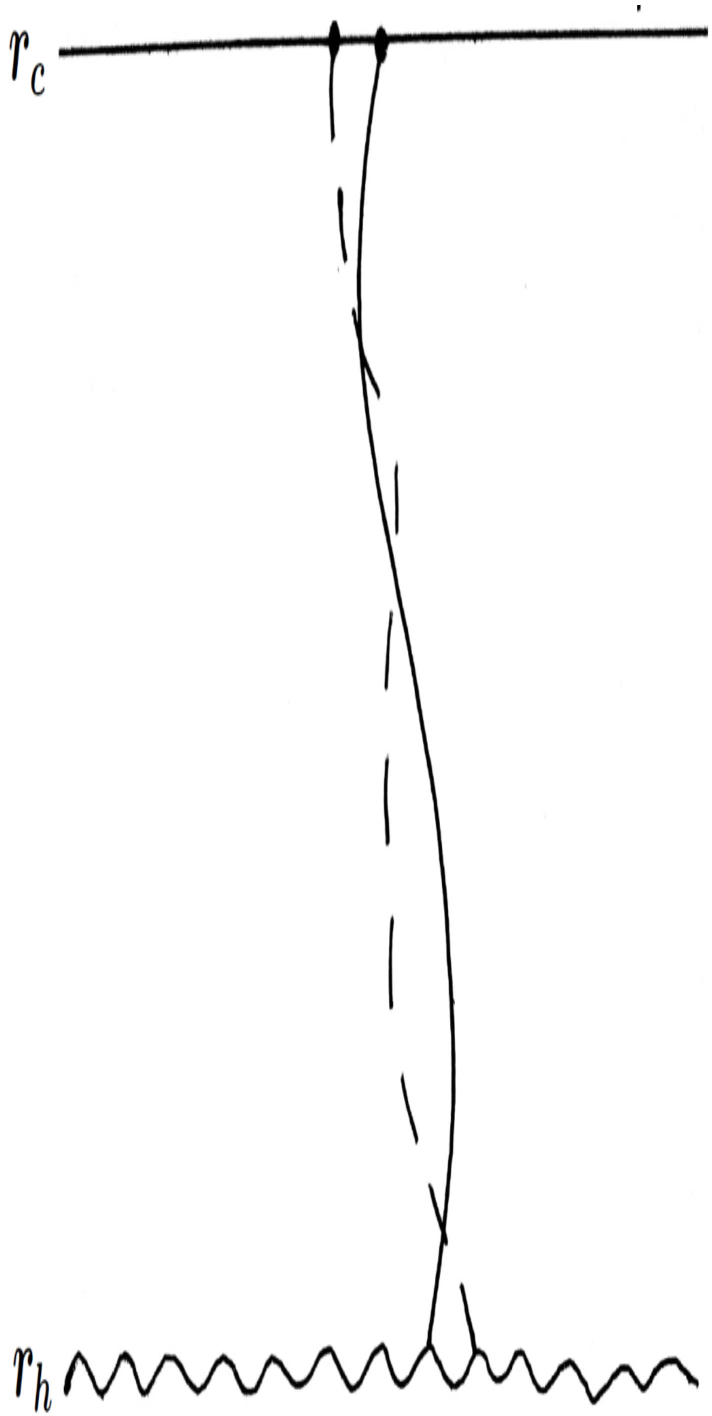
$$X_{cl} = 0$$



String embedded in BTZ background

$$ds^2 = -\left(r^2 - r_h^2\right) dt^2 + \frac{dr^2}{\left(r^2 - r_h^2\right)} + r^2 dx^2$$

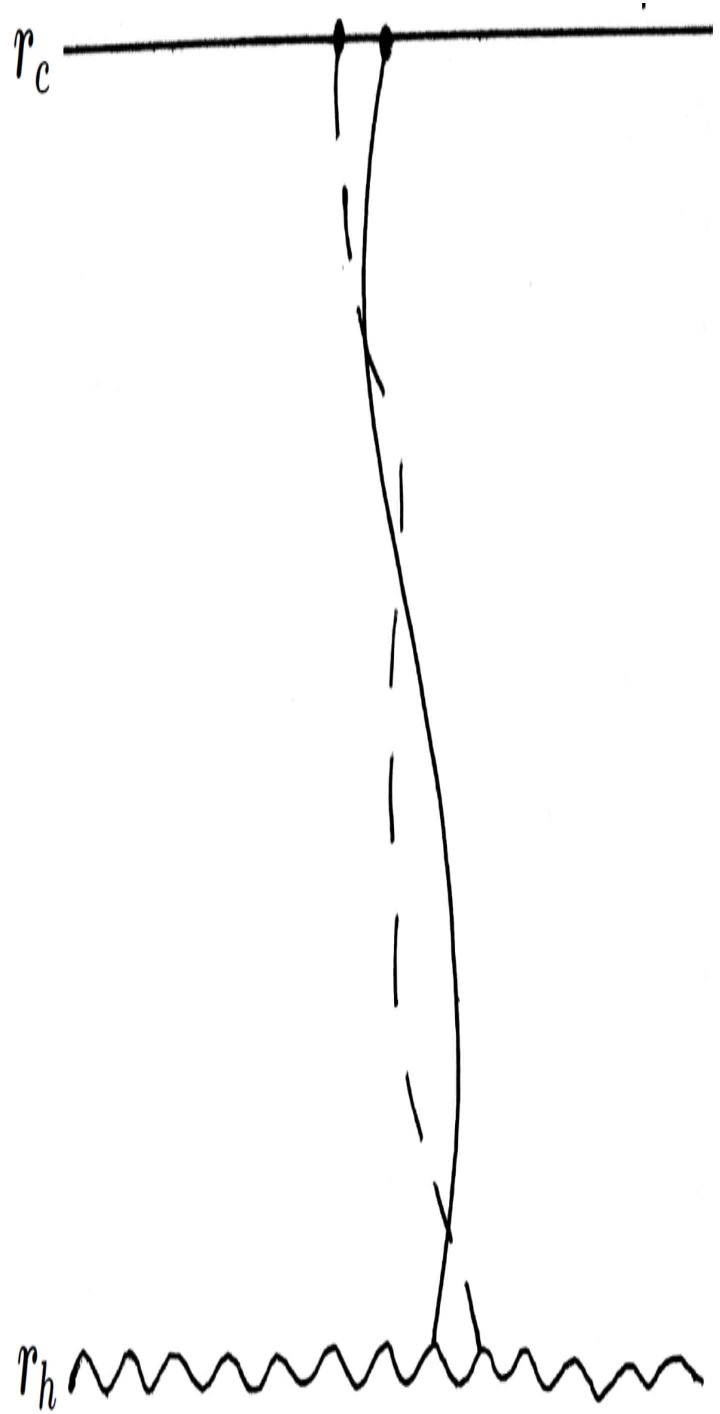
$$X_{cl} = 0 \quad \Rightarrow \quad AdS_2 \; w.s$$



String embedded in BTZ background

$$ds^2 = -\left(r^2 - r_h^2\right) dt^2 + \frac{dr^2}{\left(r^2 - r_h^2\right)} + r^2 dx^2$$

$$X_{cl} = 0 \quad \Rightarrow \quad AdS_2 \ w.s$$

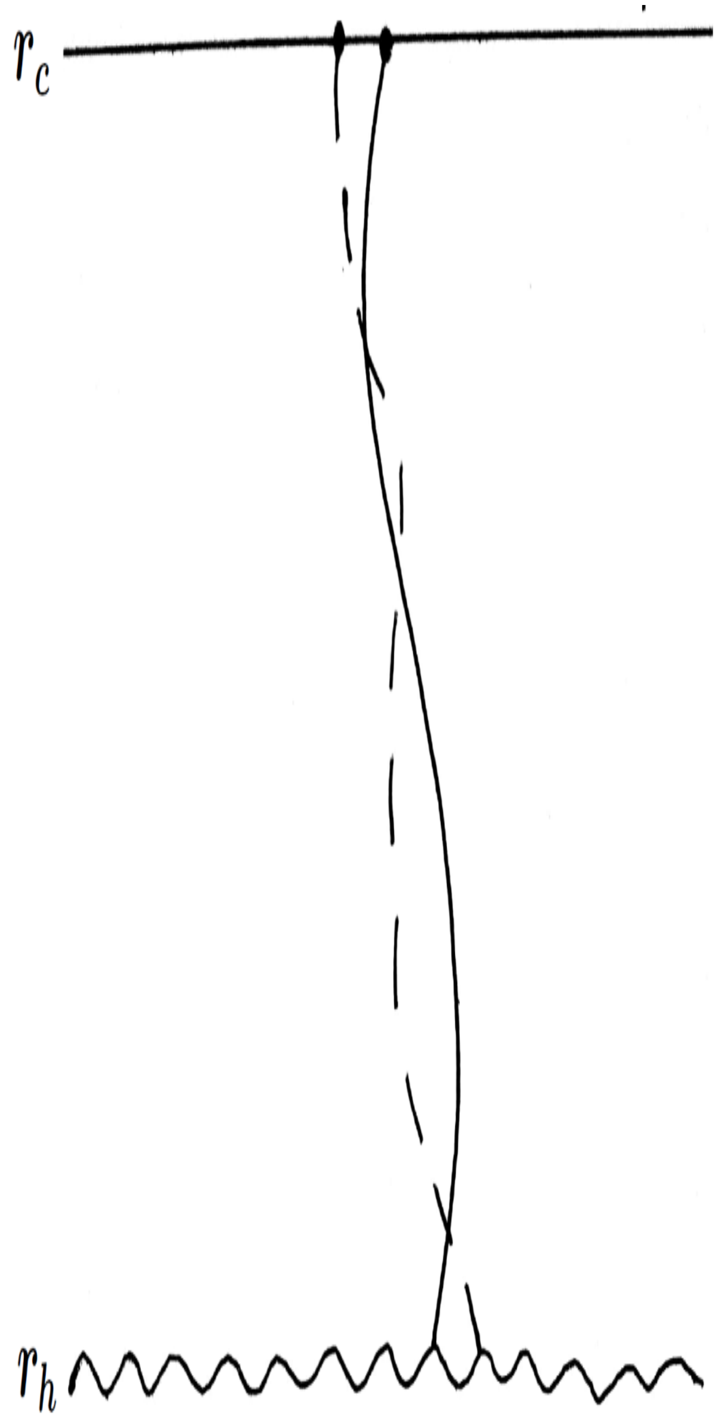


String embedded in BTZ background

$$ds^2 = -\left(r^2 - r_h^2\right) dt^2 + \frac{dr^2}{\left(r^2 - r_h^2\right)} + r^2 dx^2$$

$$X_{cl} = 0 \quad \Rightarrow \quad AdS_2 \ w.s$$

$$x = X_{cl} + \delta X$$



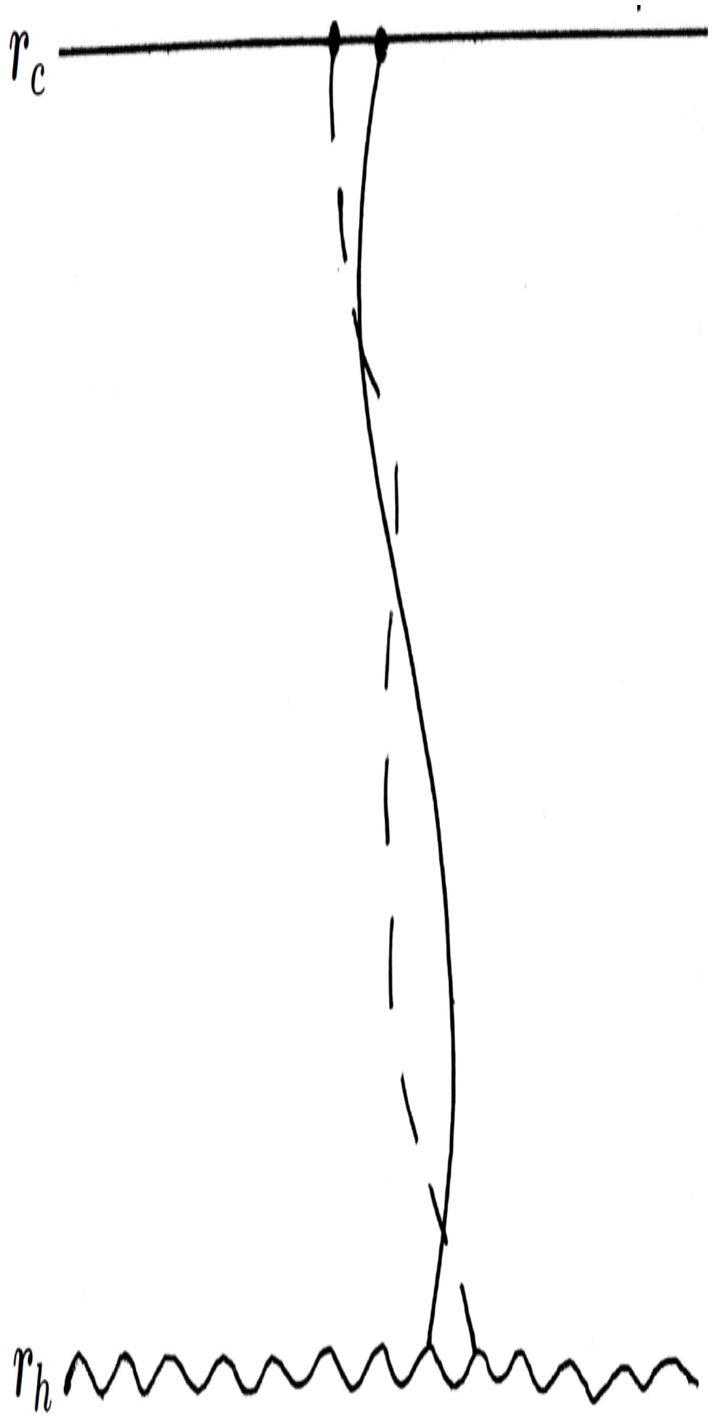
String embedded in BTZ background

$$ds^2 = -\left(r^2 - r_h^2\right) dt^2 + \frac{dr^2}{\left(r^2 - r_h^2\right)} + r^2 dx^2$$

$$X_{cl} = 0 \quad \Rightarrow \quad AdS_2 \ w.s$$

$$x = X_{cl} + \delta X$$

$$\left\langle \dot{X}(0, r_c) \, X(t, r_c) \, \dot{X}(0, r_c) \, X(t, r_c) \right\rangle$$



String embedded in BTZ background

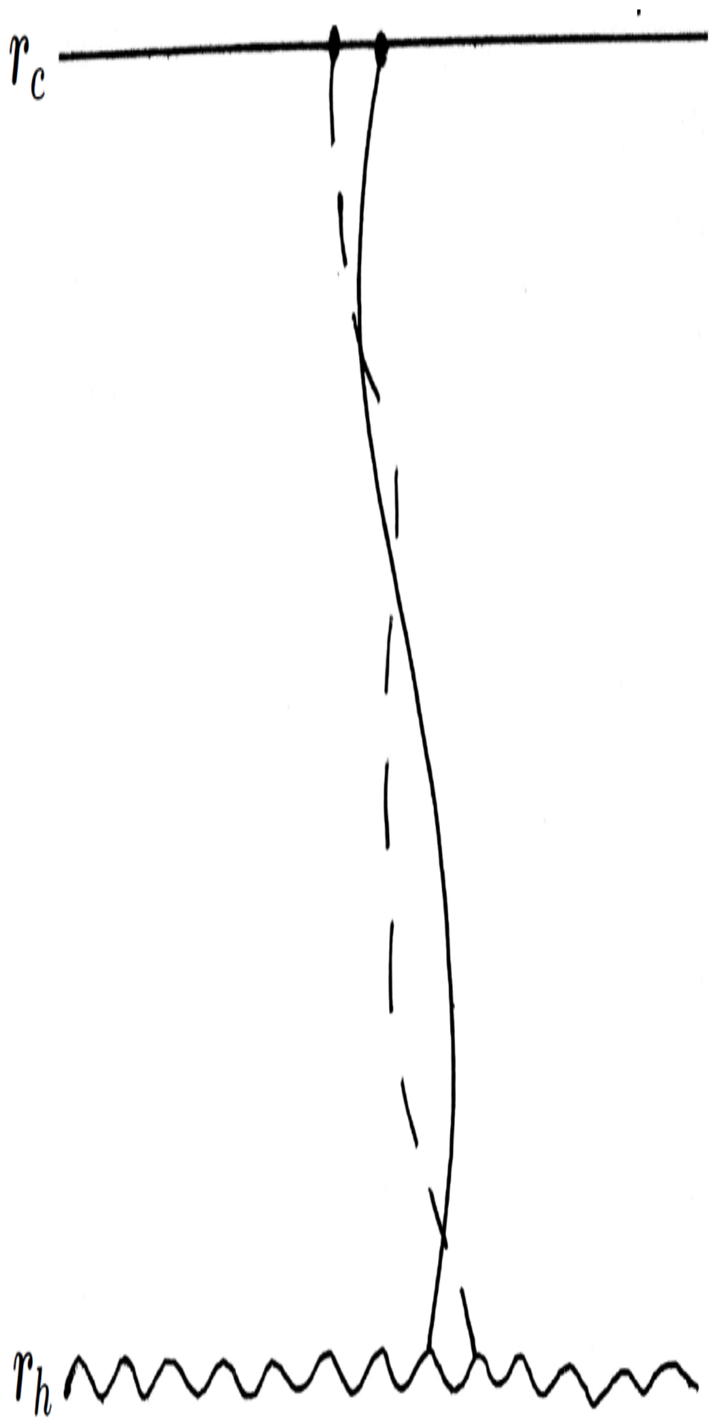
$$ds^2 = -\left(r^2 - r_h^2\right) dt^2 + \frac{dr^2}{\left(r^2 - r_h^2\right)} + r^2 dx^2$$

$$X_{cl} = 0 \quad \Rightarrow \quad AdS_2 \; w.s$$

$$x = X_{cl} + \delta X$$

$$\left\langle \dot{X}(0, r_c)\, X(t, r_c)\, \dot{X}(0, r_c)\, X(t, r_c) \right\rangle$$

$$\approx 1 - \pi l_s^2 \, e^{\frac{2\pi}{\beta} t}$$



String embedded in BTZ background

$$ds^2 = -\left(r^2 - r_h^2\right) dt^2 + \frac{dr^2}{\left(r^2 - r_h^2\right)} + r^2 dx^2$$

$$X_{cl} = 0 \quad \Rightarrow \quad AdS_2 \; w.s$$

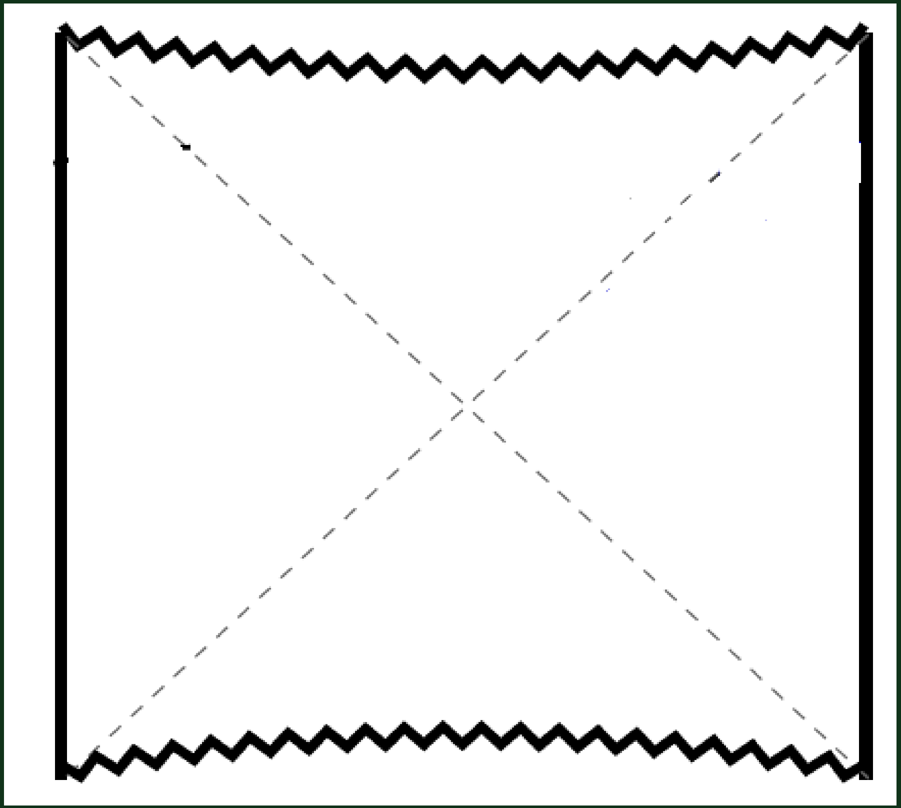
$$x = X_{cl} + \delta X$$

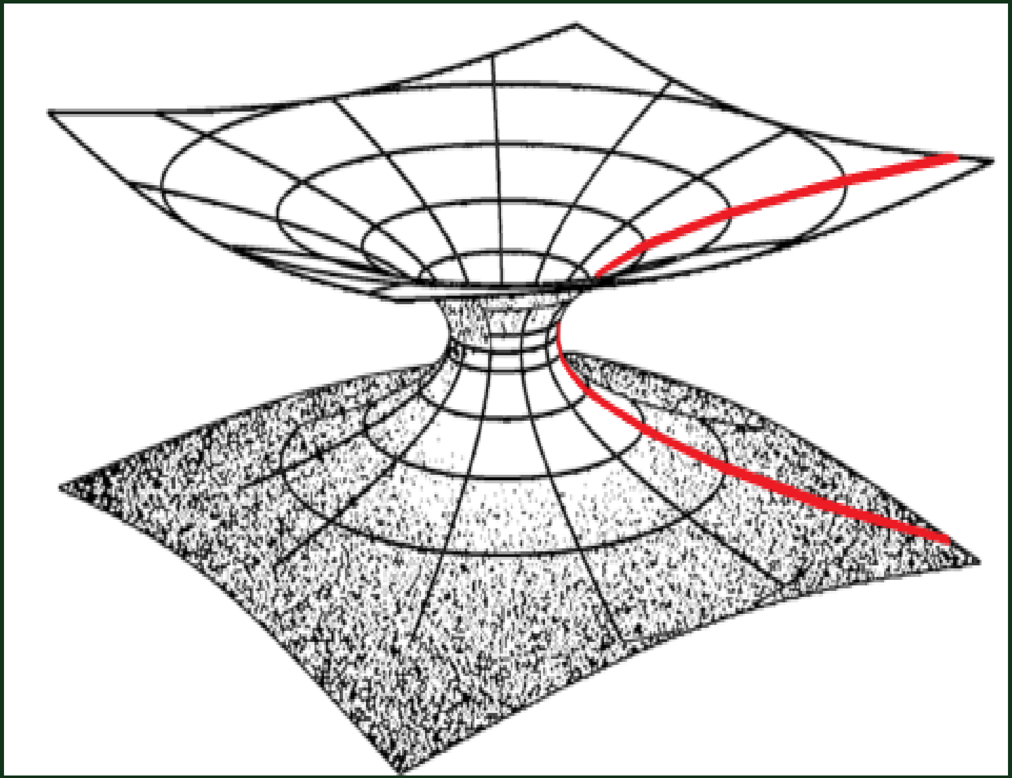
$$\left\langle \dot{X}(0, r_c)\, X(t, r_c)\, \dot{X}(0, r_c)\, X(t, r_c) \right\rangle$$

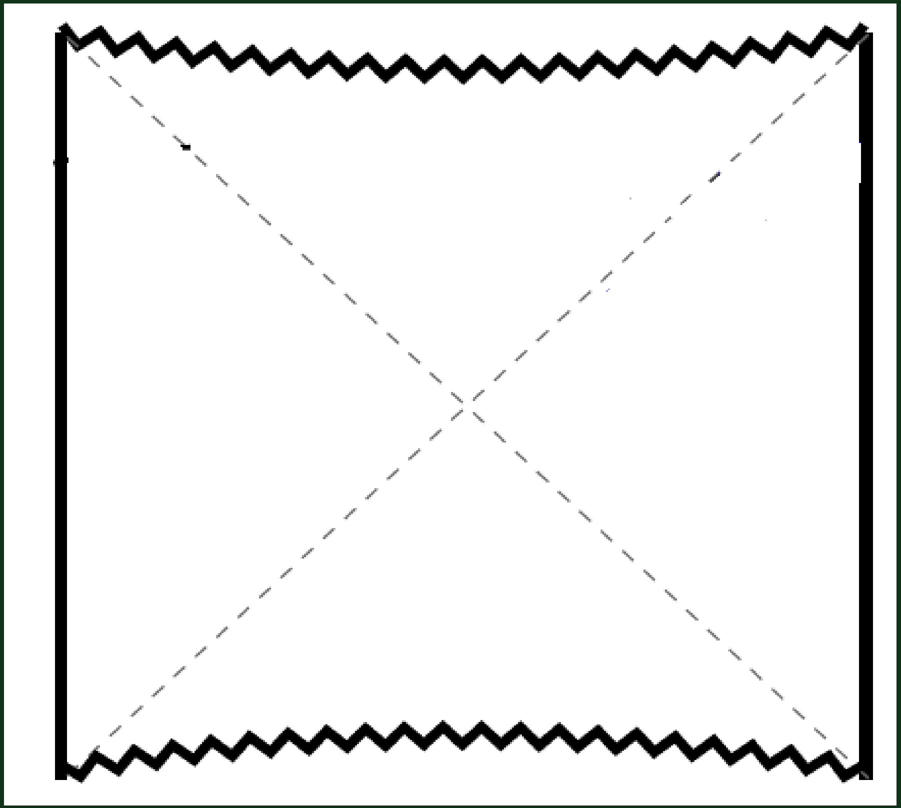
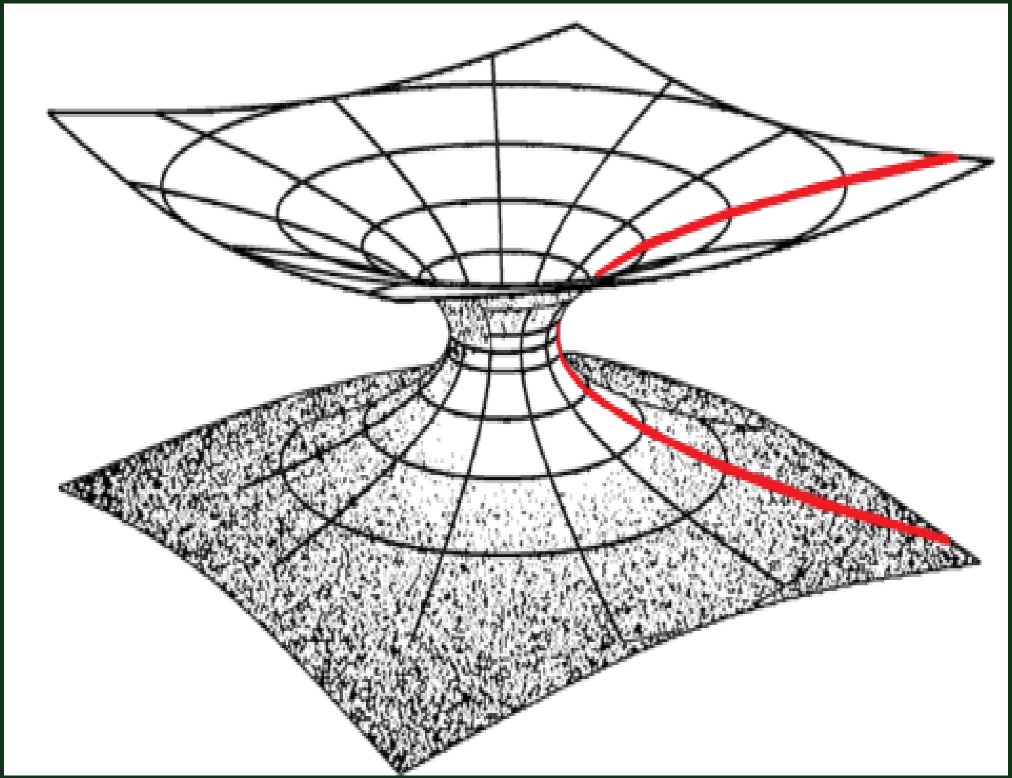
$$\approx 1 - \pi l_s^2 \, e^{\frac{2\pi}{\beta}\, t}$$

$$t_{sc} \sim \beta \log\left(\sqrt{\lambda}\right)$$

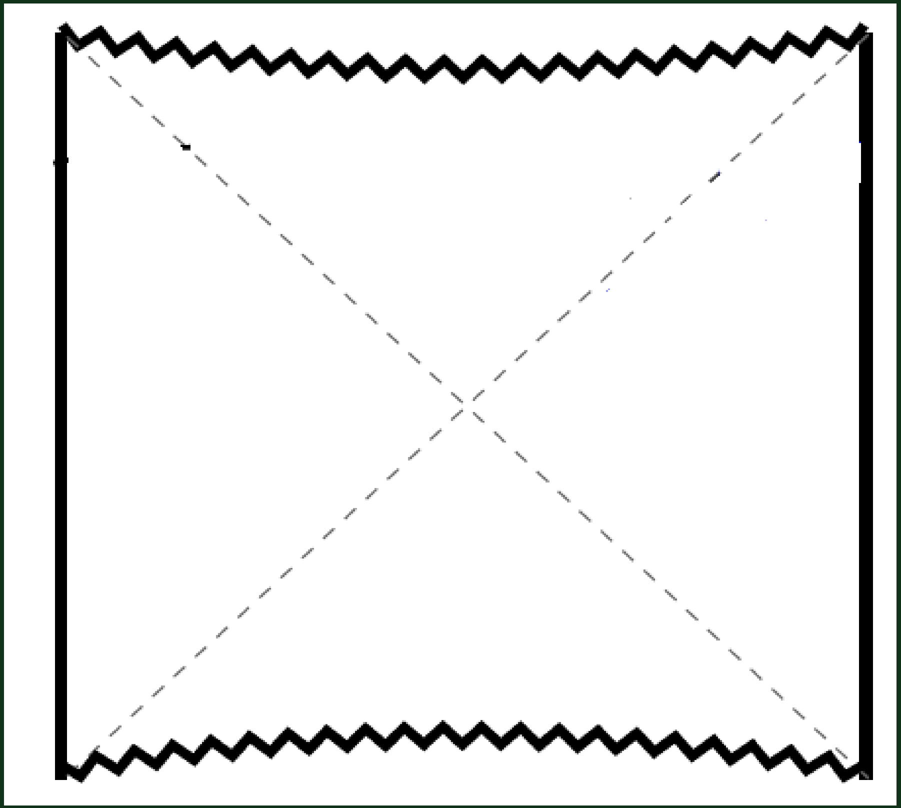
de Boer et al.

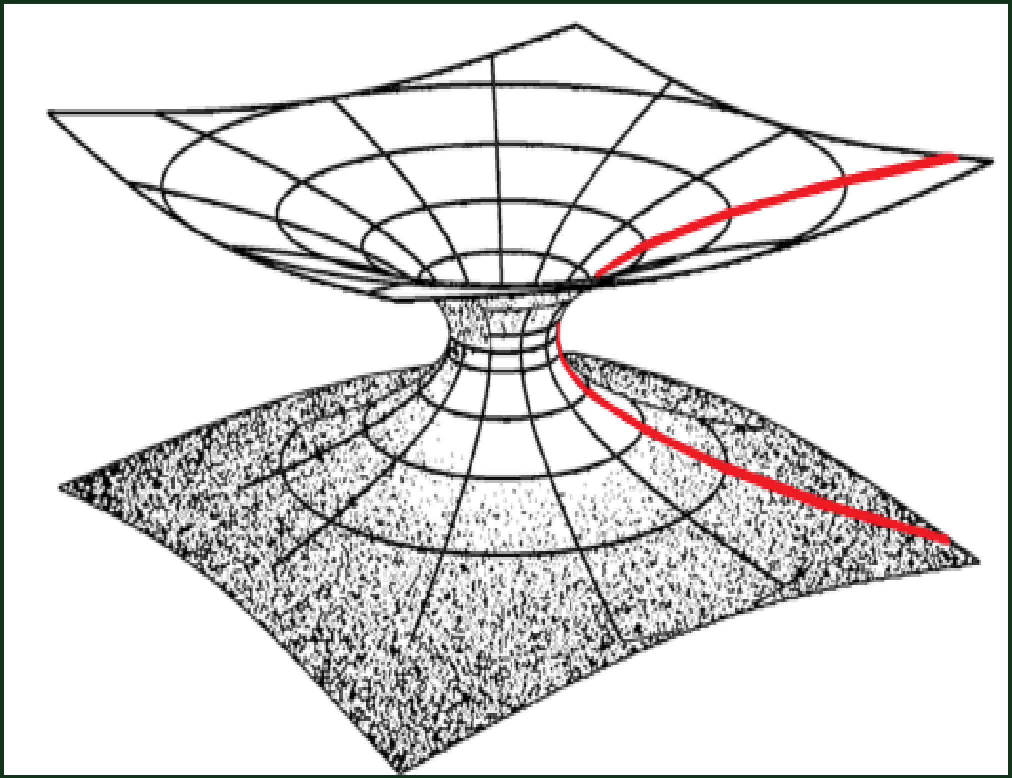




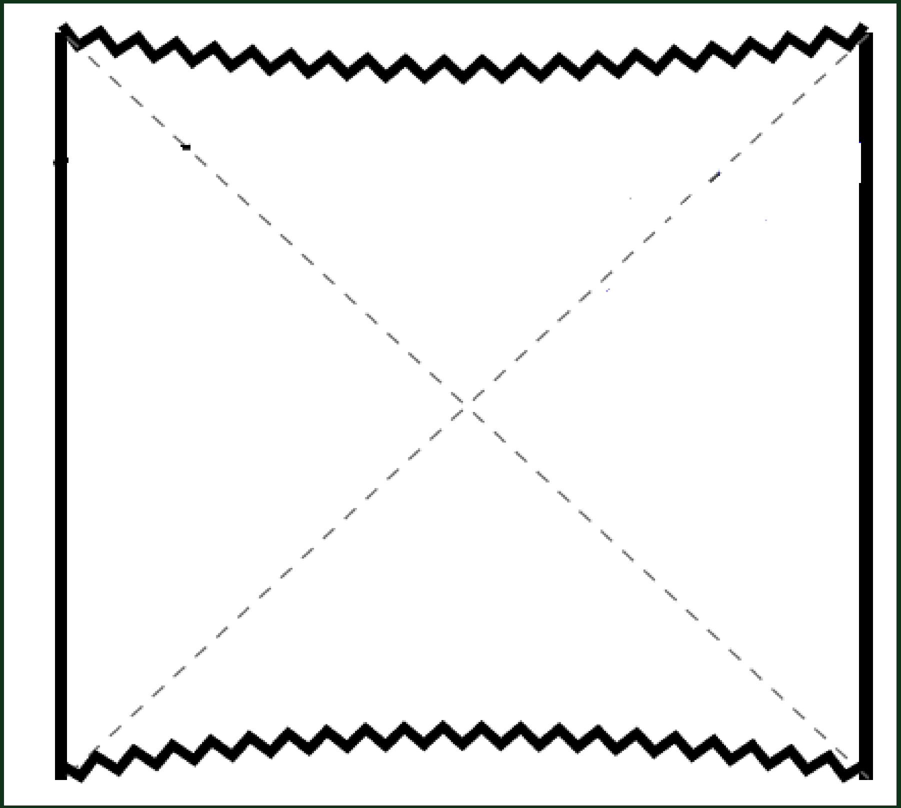
 

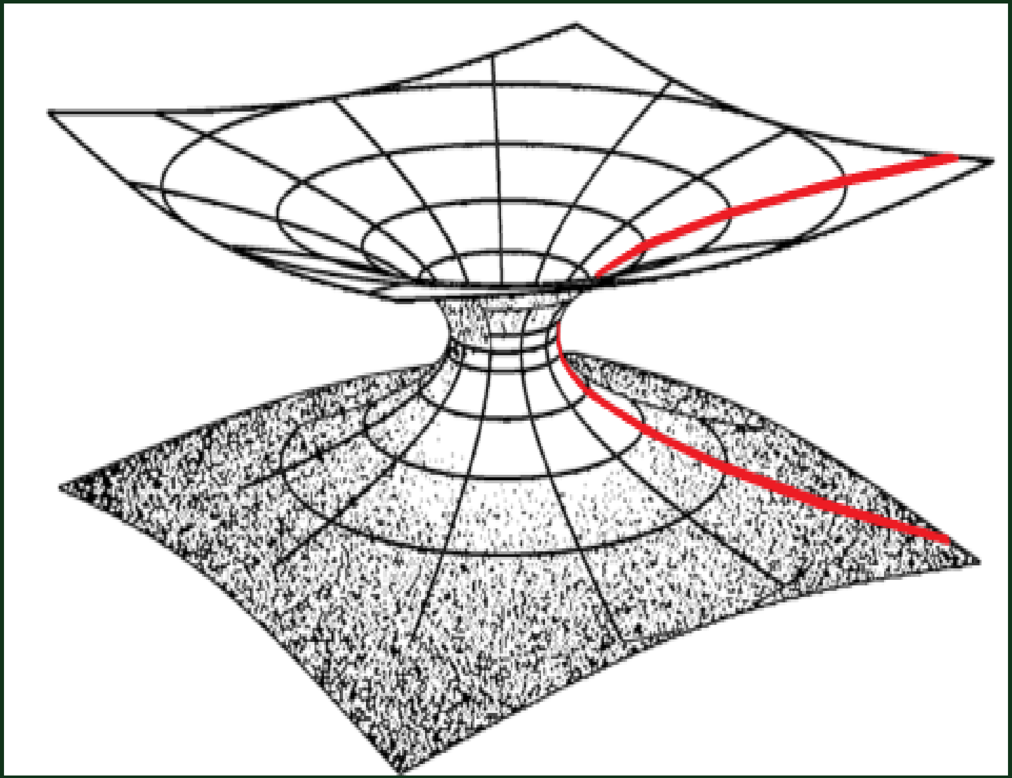
Gravity Side	Field theory side





Gravity Side	Field theory side
Is black hole background essential?	What if the background plasma is at zero temperature





Gravity Side	Field theory side
Is black hole background essential?	What if the background plasma is at zero temperature
Do vectors fluctuations saturate the bound as well?	Fluctuations of vector mesons?

$D3_N - D5_M (N >> M)$

$D3_N - D5_M (N >> M)$

	r	t	x^1	x^2	x^3	ψ	θ	ϕ	χ	ζ
D3	×	✓	✓	✓	✓	×	×	×	×	×
D5	✓	✓	✓	✓	×	×	✓	✓	×	×

$D3_N - D5_M (N >> M)$

	r	t	x^1	x^2	x^3	ψ	θ	ϕ	χ	ζ
D3	×	✓	✓	✓	✓	×	×	×	×	×
D5	✓	✓	✓	✓	×	×	✓	✓	×	×

$$ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\bar{x}^2\right) + \frac{R^2}{r^2} dr^2 + R^2 d\Omega_5^2$$

$D3_N - D5_M (N >> M)$

	r	t	x^1	x^2	x^3	ψ	θ	ϕ	χ	ζ
D3	×	✓	✓	✓	✓	×	×	×	×	×
D5	✓	✓	✓	✓	×	×	✓	✓	×	×

$$ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\bar{x}^2\right) + \frac{R^2}{r^2}dr^2 + R^2 d\Omega_5^2 \longrightarrow \boxed{T = 0}$$

$D3_N - D5_M(N >> M)$

	r	t	x^1	x^2	x^3	ψ	θ	ϕ	χ	ζ
D3	×	✓	✓	✓	✓	×	×	×	×	×
D5	✓	✓	✓	✓	×	×	✓	✓	×	×

$$ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\bar{x}^2\right) + \frac{R^2}{r^2}dr^2 + R^2 d\Omega_5^2 \longrightarrow \boxed{T = 0}$$

$$S_{D5} = -\tau_5 \int d^6y \sqrt{-det\left(P[g] + F\right)}$$

$D3_N - D5_M (N >> M)$

	r	t	x^1	x^2	x^3	ψ	θ	ϕ	χ	ζ
D3	$\times$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\times$	$\times$	$\times$	$\times$	$\times$
D5	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\times$	$\times$	$\checkmark$	$\checkmark$	$\times$	$\times$

$$ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\bar{x}^2\right) + \frac{R^2}{r^2} dr^2 + R^2 d\Omega_5^2 \longrightarrow \boxed{T = 0}$$

$$S_{D5} = -\tau_5 \int d^6 y \sqrt{-det\left(P[g] + F\right)} \longrightarrow \{X, A_\mu\}$$

$D3_N - D5_M (N >> M)$

	r	t	x^1	x^2	x^3	ψ	θ	ϕ	χ	ζ
D3	×	✓	✓	✓	✓	×	×	×	×	×
D5	✓	✓	✓	✓	×	×	✓	✓	×	×

$$ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\bar{x}^2\right) + \frac{R^2}{r^2}dr^2 + R^2 d\Omega_5^2 \longrightarrow \boxed{T = 0}$$

$$S_{D5} = -\tau_5 \int d^6y \sqrt{-det\left(P[g] + F\right)} \longrightarrow \{X, A_\mu\}$$

Fluctuation on the brane perceive an effective geometry $S_{ab} = P[g]_{ab} - \left(F.P[g]^{-1}.F\right)_{ab}$

$D3_N - D5_M (N >> M)$

	r	t	x^1	x^2	x^3	ψ	θ	ϕ	χ	ζ
D3	×	✓	✓	✓	✓	×	×	×	×	×
D5	✓	✓	✓	✓	×	×	✓	✓	×	×

$$ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\bar{x}^2\right) + \frac{R^2}{r^2}dr^2 + R^2 d\Omega_5^2 \longrightarrow \boxed{T = 0}$$

$$S_{D5} = -\tau_5 \int d^6y \sqrt{-det\left(P[g] + F\right)} \longrightarrow \{X, A_\mu\}$$

Fluctuation on the brane perceive an effective geometry $S_{ab} = P[g]_{ab} - (F.P[g]^{-1}.F)_{ab}$

$$ds^2_{osm} = -\frac{r^4 - r_s^4}{R^2 r^2}dt^2 + \frac{R^2 r^2}{r^4 - r_s^4}dr^2 + \frac{r^2}{R^2}\left(dx_1^2 + dx_2^2\right) + R^2 \; d\Omega_2^2$$

$D3_N - D5_M (N >> M)$

	r	t	x^1	x^2	x^3	ψ	θ	ϕ	χ	ζ
D3	×	✓	✓	✓	✓	×	×	×	×	×
D5	✓	✓	✓	✓	×	×	✓	✓	×	×

$$ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\bar{x}^2\right) + \frac{R^2}{r^2} dr^2 + R^2 d\Omega_5^2 \longrightarrow \boxed{T = 0}$$

$$S_{D5} = -\tau_5 \int d^6 y \sqrt{-det\left(P[g] + F\right)} \longrightarrow \{X, A_\mu\}$$

Fluctuation on the brane perceive an effective geometry $S_{ab} = P[g]_{ab} - \left(F.P[g]^{-1}.F\right)_{ab}$

$$ds^2_{osm} = -\frac{r^4 - r_s^4}{R^2 r^2} dt^2 + \frac{R^2 r^2}{r^4 - r_s^4} dr^2 + \frac{r^2}{R^2}\left(dx_1^2 + dx_2^2\right) + R^2\ d\Omega_2^2$$

$$\boxed{r_s^4 = E^2 R^4}$$

$D3_N - D5_M (N >> M)$

	r	t	x^1	x^2	x^3	ψ	θ	ϕ	χ	ζ
D3	×	✓	✓	✓	✓	×	×	×	×	×
D5	✓	✓	✓	✓	×	×	✓	✓	×	×

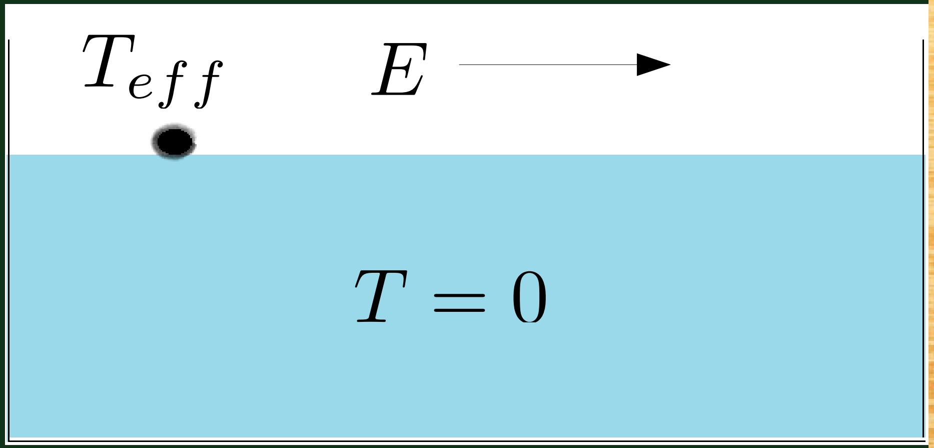
$$ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\bar{x}^2\right) + \frac{R^2}{r^2} dr^2 + R^2 d\Omega_5^2 \longrightarrow \boxed{T = 0}$$

$$S_{D5} = -\tau_5 \int d^6 y \sqrt{-det\left(P[g] + F\right)} \longrightarrow \{X, A_\mu\}$$

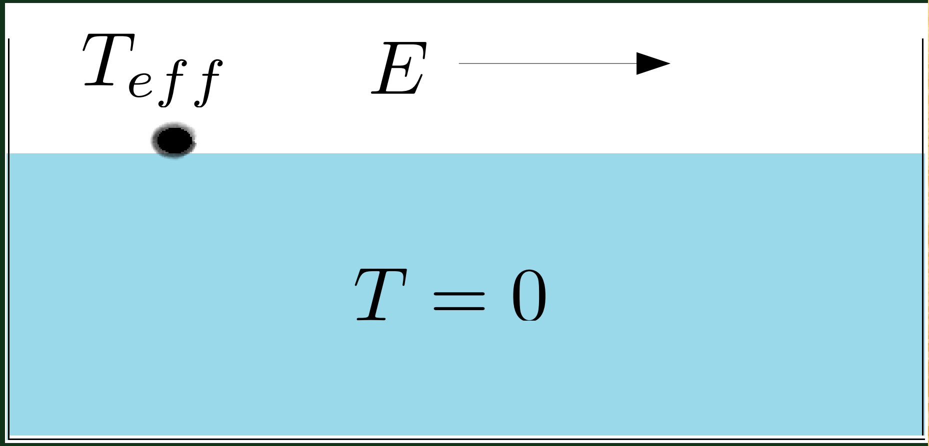
Fluctuation on the brane perceive an effective geometry $S_{ab} = P[g]_{ab} - \left(F.P[g]^{-1}.F\right)_{ab}$

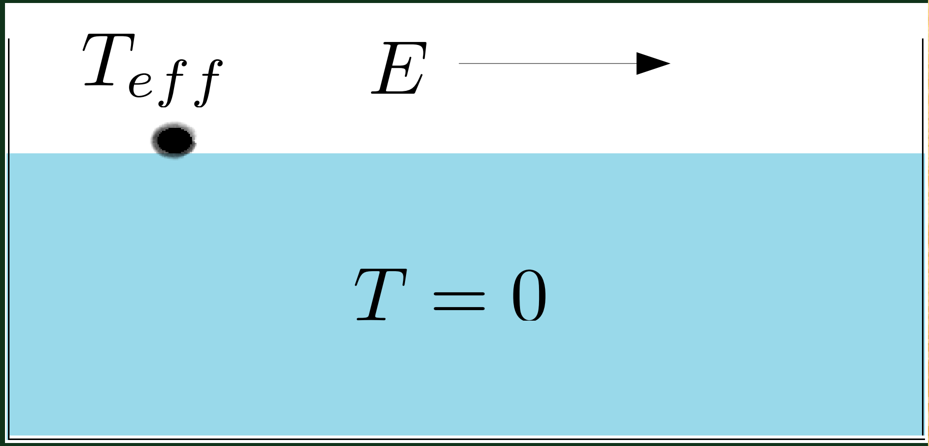
$$ds^2_{osm} = -\frac{r^4 - r_s^4}{R^2 r^2} dt^2 + \frac{R^2 r^2}{r^4 - r_s^4} dr^2 + \frac{r^2}{R^2}\left(dx_1^2 + dx_2^2\right) + R^2\ d\Omega_2^2$$

$$\boxed{r_s^4 = E^2 R^4} \qquad \boxed{T_{eff} \sim \sqrt{E}}$$


T_{eff}
E
$T = 0$

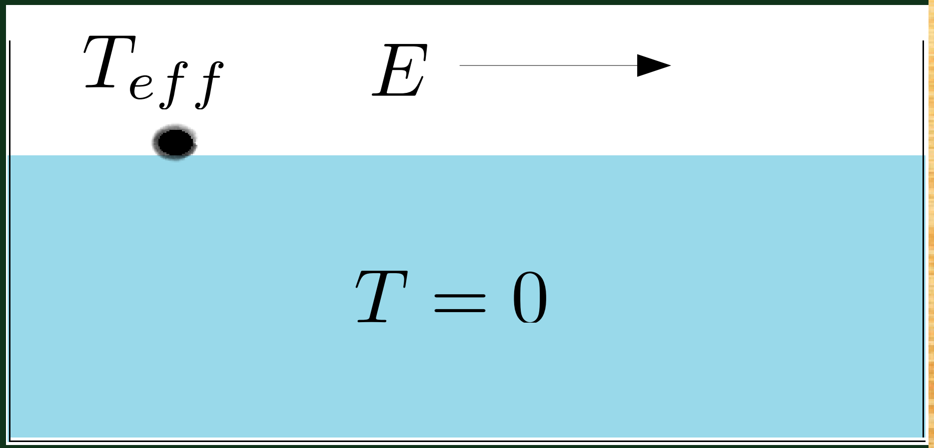
$$A(r,t) = A_{cl}(r,t) + \delta A(r,t)$$





$$A(r,t) = A_{cl}(r,t) + \delta A(r,t)$$

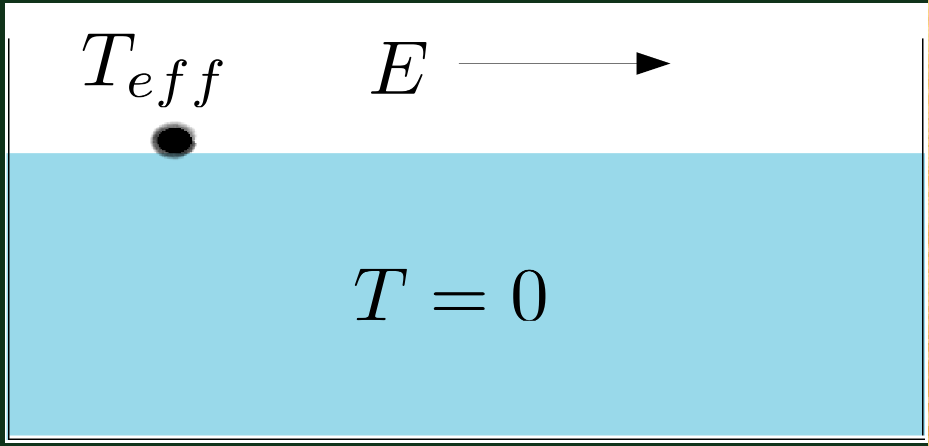
$$\frac{\left\langle \hat{A}(i\epsilon_1)\ \hat{A}(t+i\epsilon_2)\ \hat{A}(i\epsilon_3)\ \hat{A}(t+i\epsilon_4)\right\rangle}{\left\langle \hat{A}(i\epsilon_1)\ \hat{A}(i\epsilon_3)\right\rangle \left\langle \hat{A}(t+i\epsilon_2)\ \hat{A}(t+i\epsilon_4)\right\rangle}$$



$$A(r,t) = A_{cl}(r,t) + \delta A(r,t)$$

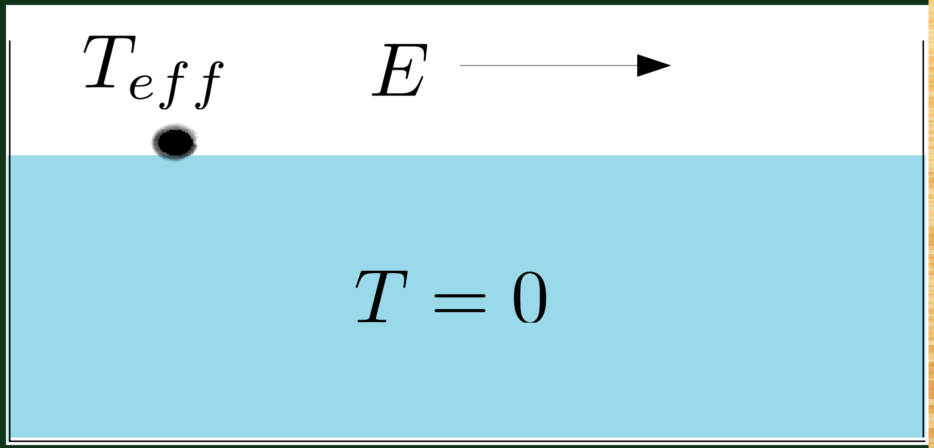
$$\frac{\left\langle \hat{A}(i\epsilon_1)\ \hat{A}(t+i\epsilon_2)\ \hat{A}(i\epsilon_3)\ \hat{A}(t+i\epsilon_4)\right\rangle}{\left\langle \hat{A}(i\epsilon_1)\ \hat{A}(i\epsilon_3)\right\rangle \left\langle \hat{A}(t+i\epsilon_2)\ \hat{A}(t+i\epsilon_4)\right\rangle} = 1 - \frac{C}{\tau_5}\, e^{2\pi T_{eff}\ t}$$

$$A(r,t) = A_{cl}(r,t) + \delta A(r,t)$$



$$\frac{\left\langle \hat{A}(i\epsilon_1)\ \hat{A}(t+i\epsilon_2)\ \hat{A}(i\epsilon_3)\ \hat{A}(t+i\epsilon_4) \right\rangle}{\left\langle \hat{A}(i\epsilon_1)\ \hat{A}(i\epsilon_3) \right\rangle \left\langle \hat{A}(t+i\epsilon_2)\ \hat{A}(t+i\epsilon_4) \right\rangle} = 1 - \frac{C}{\tau_5}\, e^{2\pi T_{eff}\ t}$$

$$t_{sc} \sim \beta_{eff} \log\left(N_c \sqrt{\lambda}\right)$$

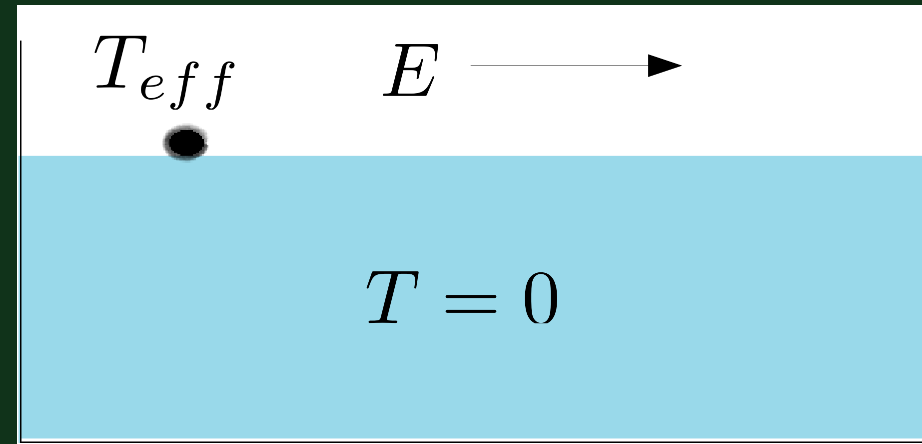


$$A(r,t) = A_{cl}(r,t) + \delta A(r,t)$$

$$\frac{\left\langle \hat{A}(i\epsilon_1)\ \hat{A}(t+i\epsilon_2)\ \hat{A}(i\epsilon_3)\ \hat{A}(t+i\epsilon_4)\right\rangle}{\left\langle \hat{A}(i\epsilon_1)\ \hat{A}(i\epsilon_3)\right\rangle \left\langle \hat{A}(t+i\epsilon_2)\ \hat{A}(t+i\epsilon_4)\right\rangle} = 1 - \frac{C}{\tau_5}\, e^{2\pi T_{eff}\ t}$$

$$t_{sc} \sim \beta_{eff} \log\left(N_c\sqrt{\lambda}\right)$$

$$t_{sc} \sim \frac{1}{2\pi T_{eff}} \log\left(N_c N_f \lambda^{\frac{p-3}{4}}\right)$$



$$A(r,t) = A_{cl}(r,t) + \delta A(r,t)$$

$$\frac{\langle \hat{A}(i\epsilon_1)\ \hat{A}(t+i\epsilon_2)\ \hat{A}(i\epsilon_3)\ \hat{A}(t+i\epsilon_4)\rangle}{\langle \hat{A}(i\epsilon_1)\ \hat{A}(i\epsilon_3)\rangle\ \langle \hat{A}(t+i\epsilon_2)\ \hat{A}(t+i\epsilon_4)\rangle} = 1 - \frac{C}{\tau_5}\, e^{2\pi T_{eff}\ t}$$

$$t_{sc} \sim \beta_{eff} \log\left(N_c\sqrt{\lambda}\right)$$

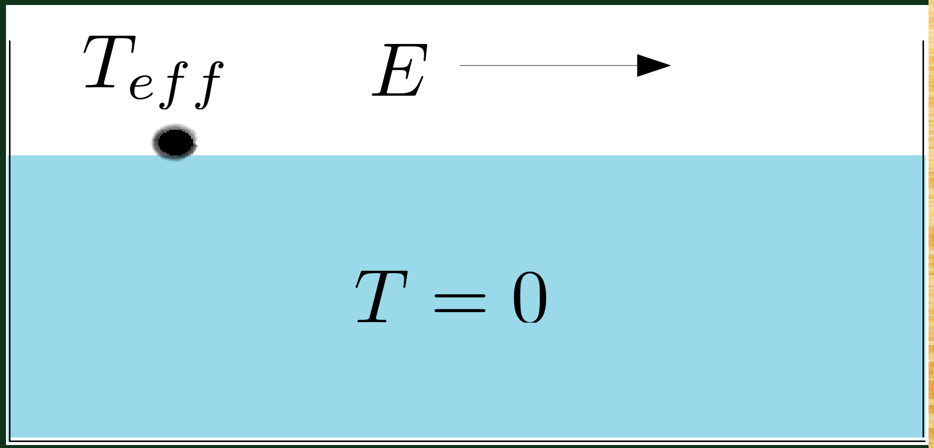
$$t_{sc} \sim \frac{1}{2\pi T_{eff}} \log\left(N_c N_f \lambda^{\frac{p-3}{4}}\right)$$

In presence of non-extremal background

$$\lambda_{brane} = 2\pi\sqrt{T^2 + E^4}$$

whereas

$$\lambda_{gravity} = 2\pi T$$



$$A(r,t) = A_{cl}(r,t) + \delta A(r,t)$$

$$\frac{\left\langle \hat{A}(i\epsilon_1)\ \hat{A}(t+i\epsilon_2)\ \hat{A}(i\epsilon_3)\ \hat{A}(t+i\epsilon_4)\right\rangle}{\left\langle \hat{A}(i\epsilon_1)\ \hat{A}(i\epsilon_3)\right\rangle \left\langle \hat{A}(t+i\epsilon_2)\ \hat{A}(t+i\epsilon_4)\right\rangle} = 1 - \frac{C}{\tau_5}\, e^{2\pi T_{eff}\ t}$$

$$t_{sc} \sim \beta_{eff} \log\left(N_c\sqrt{\lambda}\right)$$

$$t_{sc} \sim \frac{1}{2\pi T_{eff}} \log\left(N_c N_f \lambda^{\frac{p-3}{4}}\right)$$

In presence of non-extremal background

$$\lambda_{brane} = 2\pi\,\sqrt{T^2 + E^4}$$

whereas

$$\lambda_{gravity} = 2\pi T$$

- Einstein gravity not essential. Even if the gluon bath is at zero temperature, flavor fluctuations independently saturate the bound.

Fluctuations	Scrambling Time (t_{sc})
Gravity (gluons)	$\beta\ log(N_c^2)$
Scalar (scalar mesons)	$\beta\ log(\sqrt{\lambda})$
Vector (vector mesons)	$\beta\ log(N_c N_f \lambda^{\frac{p-3}{4}})$

Open Questions

Open Questions

1. Interesting to explore the bound when the quarks interact strongly with the thermal bath.

Open Questions

1. Interesting to explore the bound when the quarks interact strongly with the thermal bath. Beyond analytic control ?!

Open Questions

1. Interesting to explore the bound when the quarks interact strongly with the thermal bath. Beyond analytic control ?!

2. The low energy dynamics of the maximally chaotic systems is governed by a Schwarzian action.

Open Questions

1. Interesting to explore the bound when the quarks interact strongly with the thermal bath. Beyond analytic control ?!

2. The low energy dynamics of the maximally chaotic systems is governed by a Schwarzian action. Low energy holographic QCD ?!

Open Questions

1. Interesting to explore the bound when the quarks interact strongly with the thermal bath. Beyond analytic control ?!

2. The low energy dynamics of the maximally chaotic systems is governed by a Schwarzian action. Low energy holographic QCD ?!

3. More realistic gauge theories with finite N_c.

Open Questions

1. Interesting to explore the bound when the quarks interact strongly with the thermal bath. Beyond analytic control ?!

2. The low energy dynamics of the maximally chaotic systems is governed by a Schwarzian action. Low energy holographic QCD ?!

3. More realistic gauge theories with finite N_c. 1/N_c corrections

Open Questions

1. Interesting to explore the bound when the quarks interact strongly with the thermal bath. Beyond analytic control ?!

2. The low energy dynamics of the maximally chaotic systems is governed by a Schwarzian action. Low energy holographic QCD ?!

3. More realistic gauge theories with finite N_c. 1/N_c corrections

4. Baryonic Fluctuations ?!

Open Questions

1. Interesting to explore the bound when the quarks interact strongly with the thermal bath. Beyond analytic control ?!

2. The low energy dynamics of the maximally chaotic systems is governed by a Schwarzian action. Low energy holographic QCD ?!

3. More realistic gauge theories with finite N_c. 1/N_c corrections

4. Baryonic Fluctuations ?!

5. Effect conserved charges added to the system. So far it has turned out that, only spacetime symmetry charges lead to violation of the bound, internal symmetry charges do not.


Thank you!