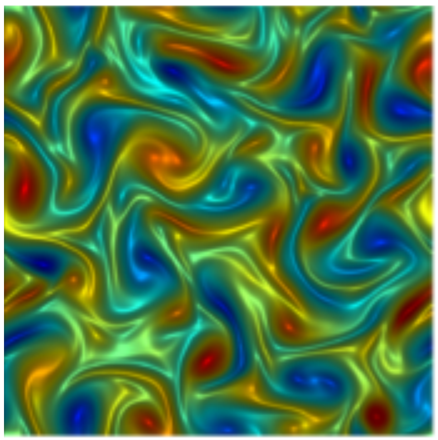
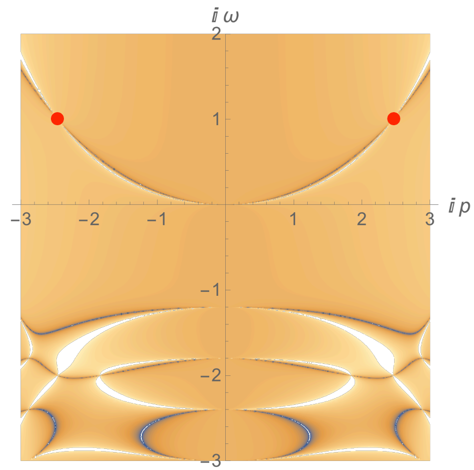
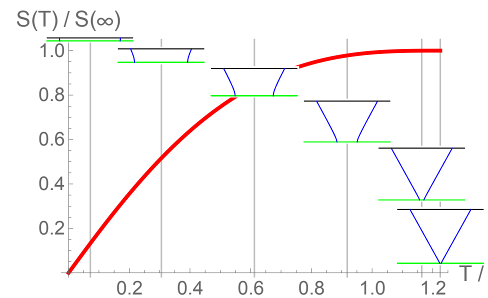
Pole skipping and related probes
away from maximal chaos







Márk Mezei (SCGP, Stony Brook)

In collaboration with: Choi, Sárosi, Stanford, van der Schee, Virrueta

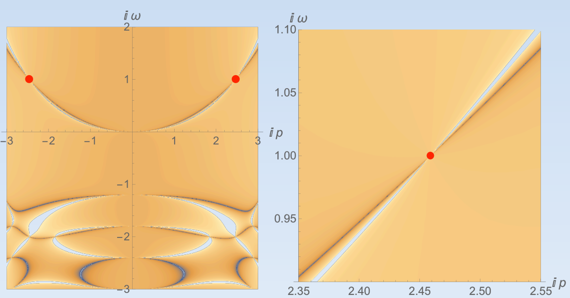
Quantum chaotic dynamics

Phenomena and signatures associated with chaotic dynamics:

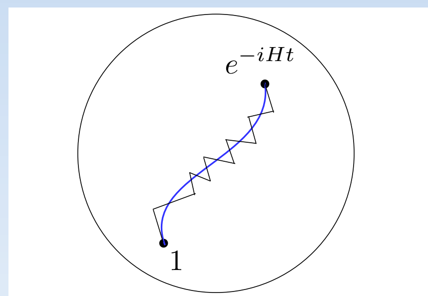
Transport

Thermalization

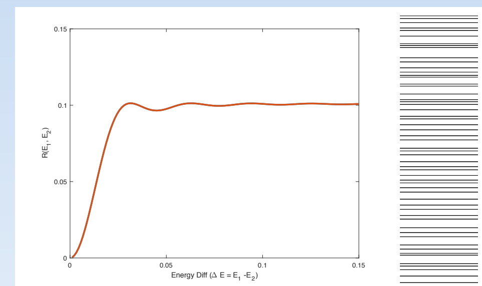
Butterfly effect



Pole skipping



Complexity growth



Eigenvalue statistics

Ultimate goal: describe these phenomena in a unified theory

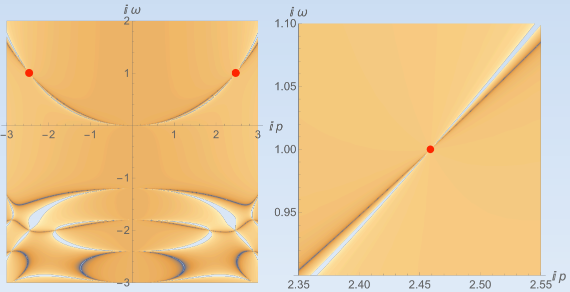
Quantum chaotic dynamics

Phenomena and signatures associated with chaotic dynamics:

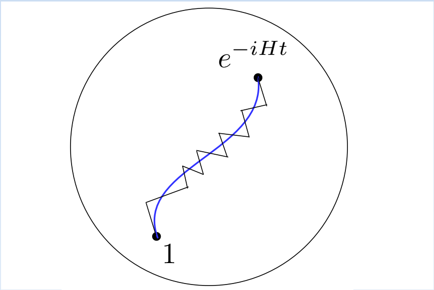
Transport

Thermalization

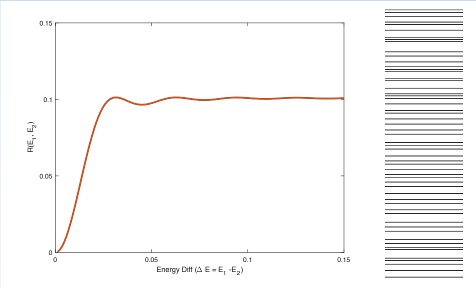
Butterfly effect



Pole skipping



Complexity growth



Eigenvalue statistics

Ultimate goal: describe these phenomena in a unified theory

Goal of talk:

- Develop EFTs at long distances and at late times for some of these processes
- Study their interplay and relation to gravity through AdS/CFT
- Go away from infinite coupling/maximal chaos

Hydrodynamics

Hydrodynamics describes transport **universally** in all chaotic systems.

- At finite temperature most excitations relax in $t_{\rm loc} \sim \beta$
  Dynamics of conserved densities T_{ab} is slow for $p\, t_{\rm loc} \ll 1$

Hydrodynamics

Hydrodynamics describes transport **universally** in all chaotic systems.

- At finite temperature most excitations relax in $t_{\rm loc} \sim \beta$
  Dynamics of conserved densities T_{ab} is slow for $p\, t_{\rm loc} \ll 1$

- Relativistic hydro from hep-th POV is an EFT based on systematic **long distance, late time** expansion. Fluid variables:

  $$T_{ab} = (\varepsilon + P) u_a u_b + P\, \eta_{ab} + \Pi_{ab}$$

  Dynamics from conservation of T_{ab}

Hydrodynamics

Hydrodynamics describes transport **universally** in all chaotic systems.

- At finite temperature most excitations relax in $t_{\rm loc} \sim \beta$
  Dynamics of conserved densities T_{ab} is slow for $p\, t_{\rm loc} \ll 1$

- Relativistic hydro from hep-th POV is an EFT based on systematic **long distance, late time** expansion. Fluid variables:

  $$T_{ab} = (\varepsilon + P) u_a u_b + P\, \eta_{ab} + \Pi_{ab}$$

  Dynamics from conservation of T_{ab}

- Correlation functions

  $$G^R_{\varepsilon\varepsilon}(\omega, p) = \frac{s}{\beta}\, \frac{p^2}{c_s^2 p^2 - \omega^2 - i\Gamma_s p^2 \omega} + \ldots$$

Hydrodynamics

Hydrodynamics describes transport **universally** in all chaotic systems.

- At finite temperature most excitations relax in $t_{\rm loc} \sim \beta$
  Dynamics of conserved densities T_{ab} is slow for $p\, t_{\rm loc} \ll 1$

- Relativistic hydro from hep-th POV is an EFT based on systematic **long distance, late time** expansion. Fluid variables:

  $$T_{ab} = (\varepsilon + P) u_a u_b + P\, \eta_{ab} + \Pi_{ab}$$

  Dynamics from conservation of T_{ab}

- Correlation functions

  $$G^R_{\varepsilon\varepsilon}(\omega, p) = \frac{s}{\beta} \, \frac{p^2}{c_s^2 p^2 - \omega^2 - i\Gamma_s p^2 \omega} + \dots$$

- Can write any operator of the microscopic theory as $\mathcal{O}_\ell \sim \partial \dots \partial T + T \partial \dots \partial T + \dots$
  Correlation functions $\langle \mathcal{O}_\ell(t,x) \mathcal{O}_\ell(0,0) \rangle_\beta$ can be computed from this

Hydrodynamics

Hydrodynamics describes transport **universally** in all chaotic systems.

- At finite temperature most excitations relax in $t_{\rm loc} \sim \beta$
  Dynamics of conserved densities T_{ab} is slow for $p\, t_{\rm loc} \ll 1$

- Relativistic hydro from hep-th POV is an EFT based on systematic **long distance, late time** expansion. Fluid variables:

  $$T_{ab} = (\varepsilon + P) u_a u_b + P\, \eta_{ab} + \Pi_{ab}$$

  Dynamics from conservation of T_{ab}

- Correlation functions

  $$G^R_{\varepsilon\varepsilon}(\omega, p) = \frac{s}{\beta} \frac{p^2}{c_s^2 p^2 - \omega^2 - i\Gamma_s p^2 \omega} + \dots$$

- Can write any operator of the microscopic theory as $\mathcal{O}_\ell \sim \partial \dots \partial T + T\partial \dots \partial T + \dots$
  Correlation functions $\langle \mathcal{O}_\ell(t,x) \mathcal{O}_\ell(0,0) \rangle_\beta$ can be computed from this

- In systems without momentum conservation:

  $$G^R_{\varepsilon\varepsilon}(\omega, p) = \frac{s}{\beta} \frac{D p^2}{-i\omega + D p^2} + \dots$$

Hydrodynamics

Hydrodynamics describes transport **universally** in all chaotic systems.

- Hydrodynamic pole

$$\omega_{\text{pole}}(p) = \begin{cases} \pm c_s p + \dots & \text{(sound)} \\ -iDp^2 + \dots & \text{(energy diffusion)} \end{cases}$$

Hydrodynamics

Hydrodynamics describes transport **universally** in all chaotic systems.

- Hydrodynamic pole

$$\omega_{\text{pole}}(p) = \begin{cases} \pm c_s p + \ldots & \text{(sound)} \\ -iDp^2 + \ldots & \text{(energy diffusion)} \end{cases}$$

- Would be nice to compute $G^R_{\varepsilon\varepsilon}(\omega, p)$ in a microscopic theory. Could study the fate of the hydrodynamic pole lines for $p\,t_{\text{loc}} \sim 1$, read off (all order) transport coefficients.

Pole skipping

- Landmark achievement of AdS/CFT: compute finite temperature correlators at infinite coupling [Policastro, Son, Starinets]

Hydrodynamics

Hydrodynamics describes transport **universally** in all chaotic systems.

- Hydrodynamic pole

$$\omega_{\text{pole}}(p) = \begin{cases} \pm c_s p + \ldots & \text{(sound)} \\ -iDp^2 + \ldots & \text{(energy diffusion)} \end{cases}$$

- Would be nice to compute $G^R_{\varepsilon\varepsilon}(\omega, p)$ in a microscopic theory. Could study the fate of the hydrodynamic pole lines for $p\, t_{\text{loc}} \sim 1$, read off (all order) transport coefficients.

Pole skipping

- Landmark achievement of AdS/CFT: compute finite temperature correlators at infinite coupling [Policastro, Son, Starinets]

- Alternative history: string theorists discover hydrodynamics by studying the fluid/gravity correspondence for bumpy AdS black holes [Bhattacharyya et al.]

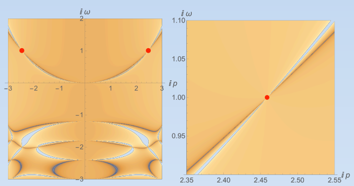
- Want to discover universal EFTs for other chaotic phenomena following the “alternative history” path

Butterfly effect

Thermalization

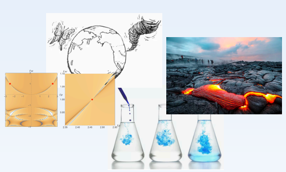
Outline

Butterfly effect
- Butterfly effect, operator growth and OTOC
- Refinement of the chaos bound



Pole skipping
- Away from maximal chaos
- Explicit thermal Green's function

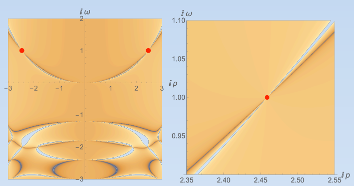
Thermalization
- Entanglement entropy as a probe
- Membrane theory is the EFT



Summary and open questions

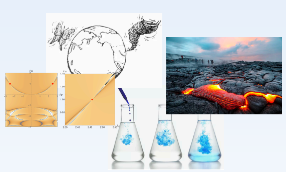
Outline

Butterfly effect
- Butterfly effect, operator growth and OTOC
- Refinement of the chaos bound



Pole skipping
- Away from maximal chaos
- Explicit thermal Green's function

Thermalization
- Entanglement entropy as a probe
- Membrane theory is the EFT



Summary and open questions

Butterfly effect, operator growth and OTOC

Butterfly effect in many-body systems: [Larkin, Ovchinnikov; Shenker, Stanford; Kitaev]

- In classical physics butterfly effect is sensitivity to initial data:

$$\delta q(t) = \delta q_0 \, e^{\lambda_L \, t}$$

- Quantum many-body context: simple operators (few-body) evolve into complex ones (many-body), one particle can have effect later in entire system.

Butterfly effect, operator growth and OTOC

Butterfly effect in many-body systems: [Larkin, Ovchinnikov; Shenker, Stanford; Kitaev]

- In classical physics butterfly effect is sensitivity to initial data:

$$\delta q(t) = \delta q_0 \, e^{\lambda_L \, t}$$

- Quantum many-body context: simple operators (few-body) evolve into complex ones (many-body), one particle can have effect later in entire system.

- Diagnostic is OTOC:

$$C(t,x) = -\frac{\langle [W(t,x), V(0)]^2 \rangle}{\langle V^2 \rangle \langle W^2 \rangle}$$

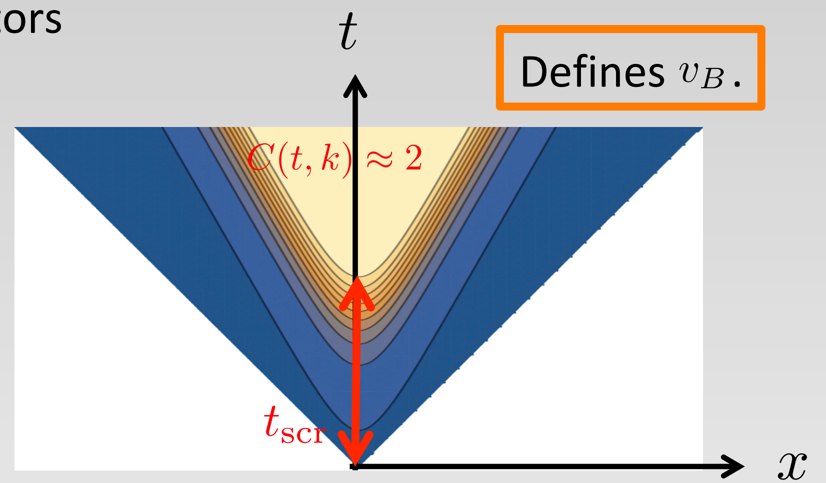
In its expansion both TO and OTO terms.

Chaotic operator growth

Effective size of an operator in a thermal state:

- Chaotic time evolution makes simple local operators complex. Size can be probed by the OTOC: [Roberts, Susskind, Stanford]

$$C(t,x) = -\frac{\langle [W(t,x),V(0)]^2\rangle}{\langle V^2\rangle\langle W^2\rangle}$$



Defines v_B.

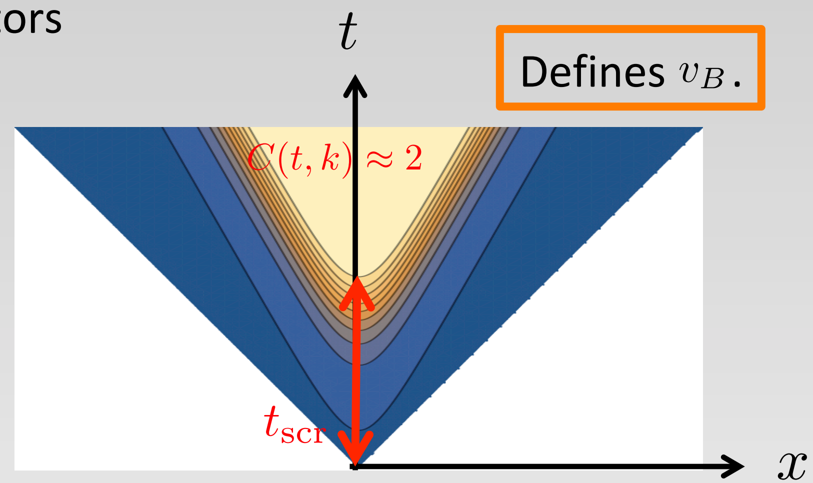
Chaotic operator growth

Effective size of an operator in a thermal state:

- Chaotic time evolution makes simple local operators complex. Size can be probed by the OTOC: [Roberts, Susskind, Stanford]

$$C(t,x) = -\frac{\langle [W(t,x), V(0)]^2 \rangle}{\langle V^2 \rangle \langle W^2 \rangle}$$

Defines v_B.

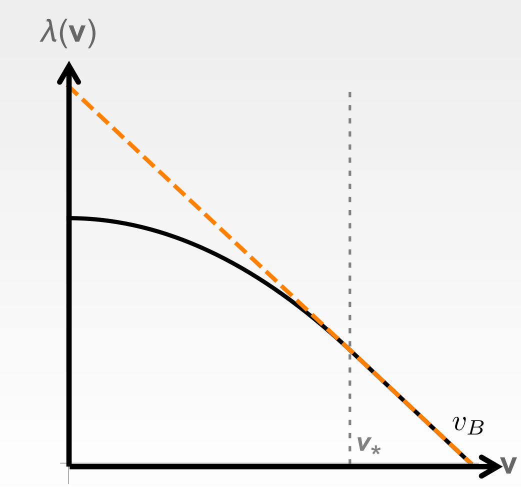


- Can compute in AdS/CFT in hydro-like regime [Shenker, Stanford]

$$C(t,x) = \frac{\#}{N^2} \exp\left[\frac{2\pi}{\beta}\left(t - |x|/v_B\right)\right] + \dots \qquad \beta \ll t, |x| \ll t_{\mathrm{scr}}$$

- Chaos bound [Maldacena, Shenker, Stanford]

$$C(t,x) = \frac{\#}{N^2} \exp\left(\lambda_L t\right) + \dots \qquad \lambda_L \leq \frac{2\pi}{\beta}$$

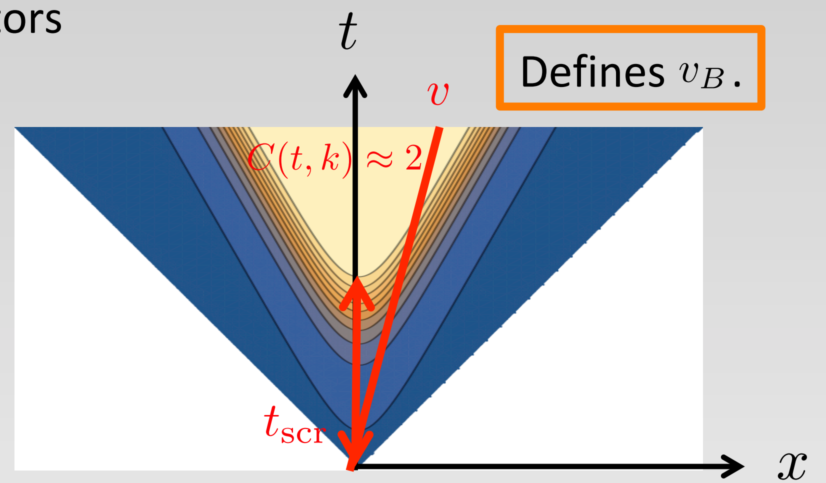


Chaotic operator growth

Effective size of an operator in a thermal state:

- Chaotic time evolution makes simple local operators complex. Size can be probed by the OTOC: [Roberts, Susskind, Stanford]

$$C(t,x) = -\frac{\langle [W(t,x),V(0)]^2\rangle}{\langle V^2\rangle\langle W^2\rangle}$$



- Can compute in AdS/CFT in hydro-like regime [Shenker, Stanford]

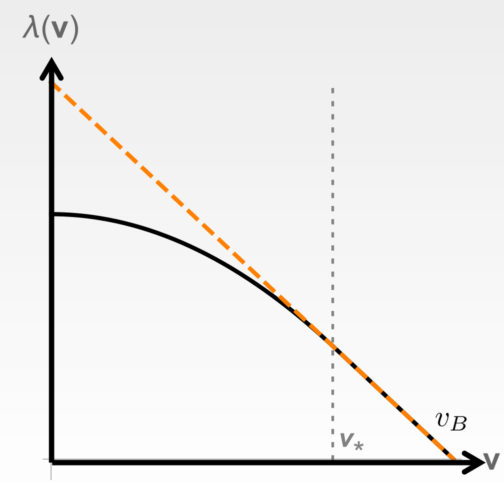
$$C(t,x) = \frac{\#}{N^2}\,\exp\left[\frac{2\pi}{\beta}\left(t-|x|/v_B\right)\right]+\dots \qquad \beta \ll t, |x| \ll t_{\text{scr}}$$

- Chaos bound [Maldacena, Shenker, Stanford]

$$C(t,x) = \frac{\#}{N^2}\,\exp\left(\lambda_L\, t\right)+\dots \qquad \boxed{\lambda_L \leq \frac{2\pi}{\beta}}$$

- Refinement: [Kemani, Huse, Nahum; Xu, Swingle; MM, Sárosi]

$$C(t,x=vt) = \frac{\#}{N^2}\,\exp\left(\lambda(v)\, t\right)+\dots \qquad \lambda(v) \leq \frac{2\pi}{\beta}\left(1-\frac{|v|}{v_B}\right)$$

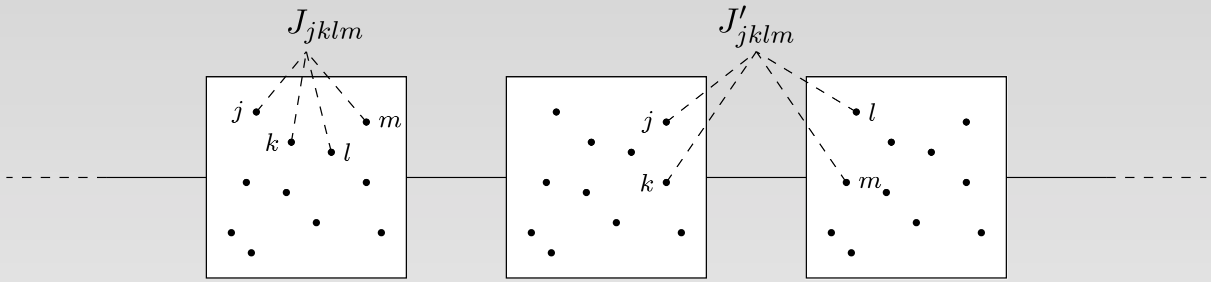


Generic velocity dependence: even when $\lambda_L < 2\pi/\beta$ for $\boxed{v \geq v_*}$ get maximal chaos.

SYK chain

The SYK model is a solvable chaotic system. It can be made spatially local [Gu, Qi, Stanford]

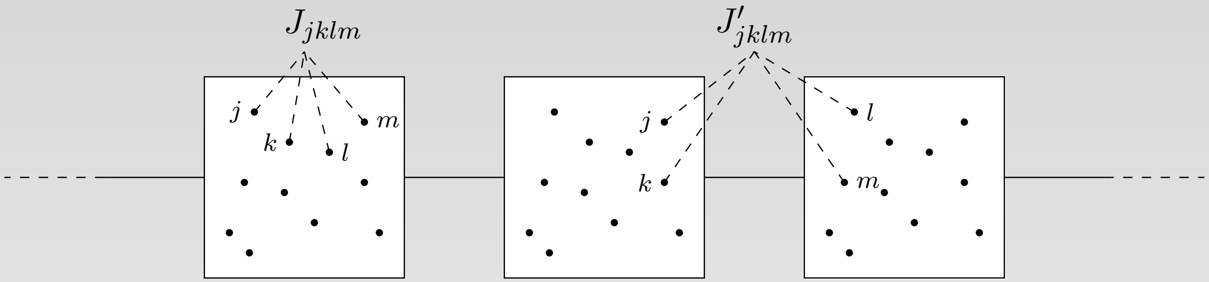
$$H = i^{q/2} \sum_x \left[\sum_{\{i_k\}} J_{i_1 \ldots i_q, x}\, \chi_{i_1,x} \cdots \chi_{i_q,x} + \sum_{\{i_k\},\{j_k\}} J'_{(i_1 \ldots i_{q/2})(j_1 \ldots j_{q/2}),x} \left(\chi_{i_1,x} \cdots \chi_{i_{q/2},x}\right) \left(\chi_{i_1,x+1} \cdots \chi_{i_{q/2},x+1}\right) \right]$$



SYK chain

The SYK model is a solvable chaotic system. It can be made spatially local [Gu, Qi, Stanford]

$$H = i^{q/2} \sum_x \Big[\sum_{\{i_k\}} J_{i_1 \dots i_q, x}\, \chi_{i_1,x} \cdots \chi_{i_q,x} + \sum_{\{i_k\},\{j_k\}} J'_{(i_1 \dots i_{q/2})(j_1 \dots j_{q/2}),x} \left(\chi_{i_1,x} \cdots \chi_{i_{q/2},x}\right) \left(\chi_{i_1,x+1} \cdots \chi_{i_{q/2},x+1}\right) \Big]$$



- The model can be solved analytically at low-T for any q or at any T for large q [Maldacena, Stanford; Cotler et al.; Streicher; Choi, MM, Sárosi]

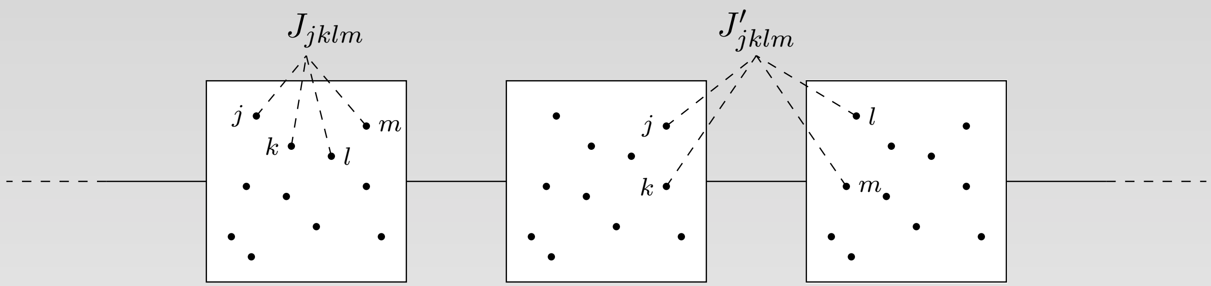
$$S_{\text{eff}} = \frac{N}{4q^2} \sum_x \int d\tau_1 d\tau_2 \left[\frac{1}{4} \partial_1 g_x \partial_2 g_x - \mathcal{J}_0^2 e^{g_x} - \mathcal{J}_1^2 e^{\frac{1}{2}(g_x + g_{x+1})} \right]$$

$$\frac{1}{N} \sum_i \chi_{i,x}(\tau_1) \chi_{i,x}(\tau_2) = \frac{\text{sgn}(\tau_{12})}{2} \left(1 + \frac{g_x(\tau_1, \tau_2)}{q} + \dots \right)$$

SYK chain

The SYK model is a solvable chaotic system. It can be made spatially local [Gu, Qi, Stanford]

$$H = i^{q/2} \sum_x \left[\sum_{\{i_k\}} J_{i_1 \dots i_q, x}\, \chi_{i_1,x} \cdots \chi_{i_q,x} + \sum_{\{i_k\},\{j_k\}} J'_{(i_1 \dots i_{q/2})(j_1 \dots j_{q/2}),x} \left(\chi_{i_1,x} \cdots \chi_{i_{q/2},x} \right) \left(\chi_{i_1,x+1} \cdots \chi_{i_{q/2},x+1} \right) \right]$$



- The model can be solved analytically at low-T for any q or at any T for large q [Maldacena, Stanford; Cotler et al.; Streicher; Choi, MM, Sárosi]

$$S_{\text{eff}} = \frac{N}{4q^2} \sum_x \int d\tau_1 d\tau_2 \left[\frac{1}{4} \partial_1 g_x \partial_2 g_x - \mathcal{J}_0^2 e^{g_x} - \mathcal{J}_1^2 e^{\frac{1}{2}(g_x + g_{x+1})} \right]$$

$$\frac{1}{N} \sum_i \chi_{i,x}(\tau_1) \chi_{i,x}(\tau_2) = \frac{\operatorname{sgn}(\tau_{12})}{2} \left(1 + \frac{g_x(\tau_1,\tau_2)}{q} + \dots \right)$$

- Saddle point gives $g_x(\tau_1,\tau_2) = g^{(s)}(\tau_{12})$ fermion propagator, $\langle \delta g_x(\tau_1,\tau_2)\, \delta g_y(\tau_3,\tau_4) \rangle$ determines the four point function [Streicher; Choi, MM, Sárosi]

Dimensionless coupling constant: $\beta \mathcal{J} \equiv \dfrac{\pi g}{\cos\left(\frac{\pi g}{2}\right)}, \quad 0 \le g < 1$

SYK chain

Effective size of an operator in a thermal state: $(\beta = 2\pi)$
[Kitaev; Maldacena, Stanford; Gu, Qi, Stanford; Choi, MM, Sárosi]

$$C(t,x) \approx \frac{\#}{N} \int dp \, \frac{\exp\left[\lambda(p)t + ipx\right]}{\cos\left(\frac{\pi\lambda(p)}{2}\right)}\,, \qquad \lambda(p) = \frac{g}{2}\left(3\sqrt{1 - 4\sin^2(p/2)} - 1\right)$$

As we change g, interpolates between free theory and maximally chaotic theory.

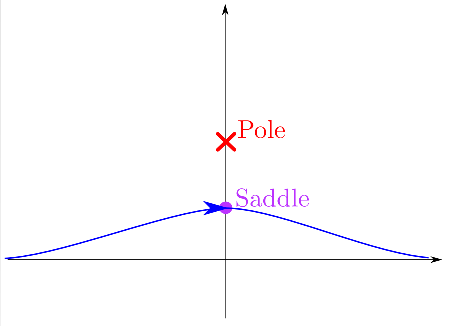
SYK chain

Effective size of an operator in a thermal state: $(\beta = 2\pi)$
[Kitaev; Maldacena, Stanford; Gu, Qi, Stanford; Choi, MM, Sárosi]

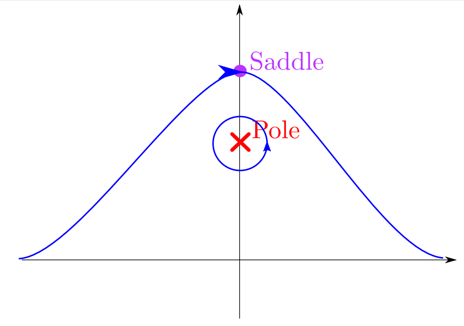
$$C(t,x) \approx \frac{\#}{N} \int dp \, \frac{\exp\left[\lambda(p)t + ipx\right]}{\cos\left(\frac{\pi\lambda(p)}{2}\right)}\,, \qquad \lambda(p) = \frac{g}{2}\left(3\sqrt{1-4\sin^2(p/2)} - 1\right)$$

As we change g, interpolates between free theory and maximally chaotic theory.

- For $\beta \ll t \ll t_{\mathrm{scr}}$, evaluate using saddle point: [Gu, Kitaev; Xu, Swingle]



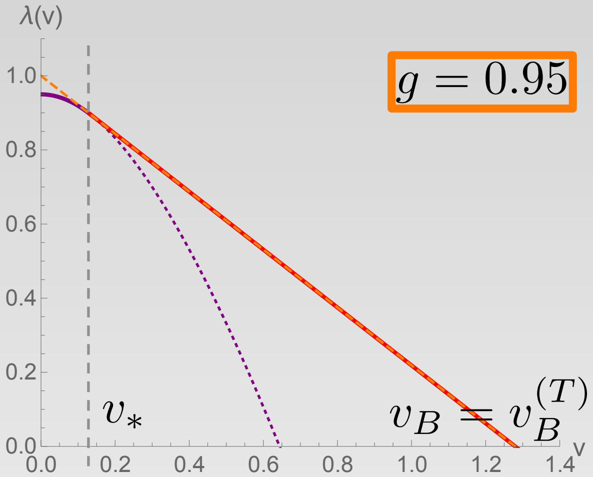
For $v < v_*$, $\lambda(v)$ is the Legendre tf. of $\lambda(p)$.

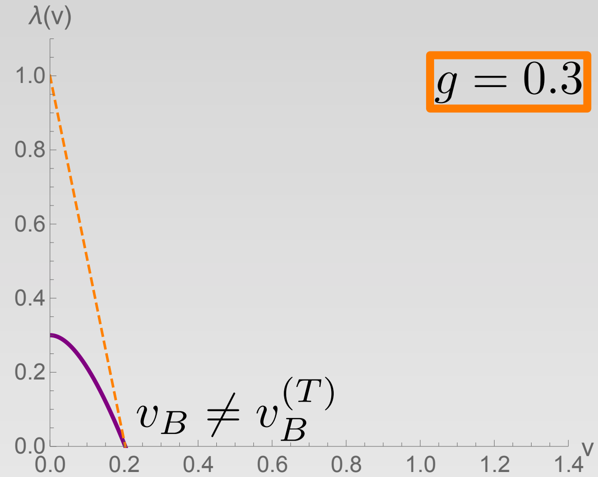


For $v \geq v_*$ "stress tensor" dominates, and chaos is maximal.

SYK chain

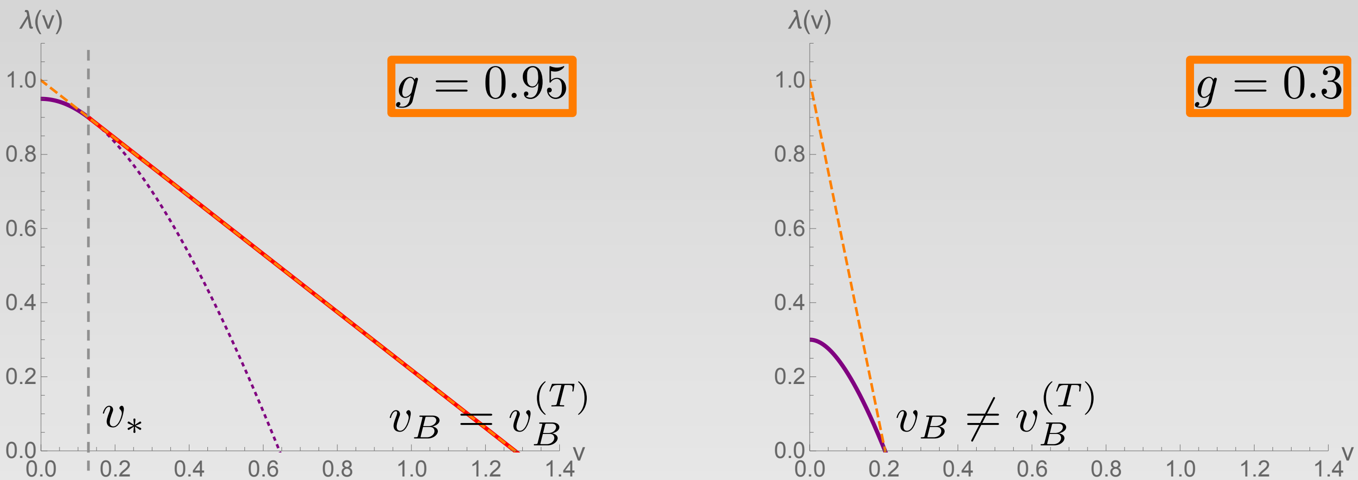
- For $v < v_*$, $\lambda(v)$ is the Legendre transform of $\lambda(p)$.
  For $v \geq v_*$ "stress tensor" dominates, and chaos is maximal.





SYK chain

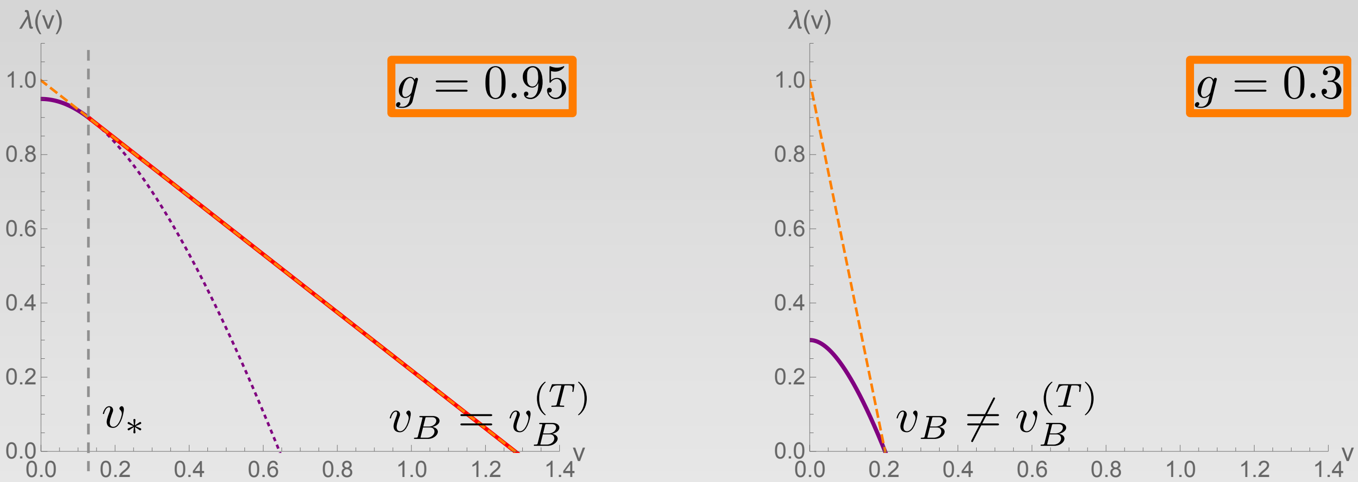
- For $v < v_*$, $\lambda(v)$ is the Legendre transform of $\lambda(p)$.
  For $v \geq v_*$ "stress tensor" dominates, and chaos is maximal.



- Similar results in CFT on $\mathbb{H}^{d-1} \times S^1$ (including 2d CFT at finite T)
  Role of $\lambda(p)$ played by leading Regge trajectory (pomeron) $j(\nu)$, known in $\mathcal{N} = 4$ SYM [Costa et al.; Gromov et al.]
  Implies that $v_B = v_B^{(T)}$ for $\lambda \geq 37.7$, and $v_B < v_B^{(T)}$ for smaller coupling.
  (Only for $\lambda \to \infty$ we get $\lambda_L = 2\pi/\beta$.)

SYK chain

- For $v < v_*$, $\lambda(v)$ is the Legendre transform of $\lambda(p)$.
  For $v \geq v_*$ "stress tensor" dominates, and chaos is maximal.

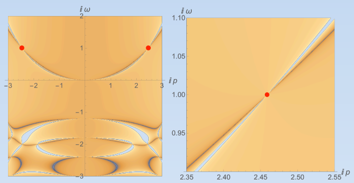


- Similar results in CFT on $\mathbb{H}^{d-1} \times S^1$ (including 2d CFT at finite T)
  Role of $\lambda(p)$ played by leading Regge trajectory (pomeron) $j(\nu)$, known in $\mathcal{N} = 4$ SYM [Costa et al.; Gromov et al.]
  Implies that $v_B = v_B^{(T)}$ for $\lambda \geq 37.7$, and $v_B < v_B^{(T)}$ for smaller coupling.
  (Only for $\lambda \to \infty$ we get $\lambda_L = 2\pi/\beta$.)

- At low-T SYK is dominated by a time reparametrization pseudo-Goldstone boson, the boundary graviton of the dual JT gravity [Kitaev; Maldacena, Stanford; Jensen; …]
  Challenge is to go away from maximal chaos [Choi, Haehl, MM, Sárosi, Streicher wip]

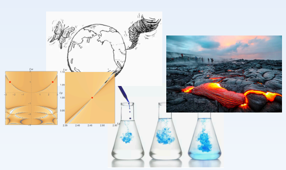
Outline

Butterfly effect
- Butterfly effect, operator growth and OTOC
- Refinement of the chaos bound



Pole skipping
- Away from maximal chaos
- Explicit thermal Green's function

Thermalization
- Entanglement entropy as a probe
- Membrane theory is the EFT



Summary and open questions

Pole skipping

OTOC motivated from operator growth. Chaos data from simpler observables?

- Recall that $G^R_{\varepsilon\varepsilon}(\omega, p)$ encodes hydro response. Family of poles

$$\omega_{\text{pole}}(p) = \begin{cases} \pm c_s p + \ldots & \text{(sound)} \\ -iDp^2 + \ldots & \text{(energy diffusion)} \end{cases}$$

Pole skipping

OTOC motivated from operator growth. Chaos data from simpler observables?

- Recall that $G^R_{\varepsilon\varepsilon}(\omega, p)$ encodes hydro response. Family of poles

$$\omega_{\rm pole}(p) = \begin{cases} \pm c_s p + \dots & \text{(sound)} \\ -iDp^2 + \dots & \text{(energy diffusion)} \end{cases}$$

- In low-T SYK can compute away from hydro regime [Gu, Qi, Stanford]

$$G^R_{\varepsilon\varepsilon}(\omega, p) = \frac{s}{\beta}\frac{Dp^2(1+\omega^2)}{-i\omega + Dp^2}$$

Pole skipping

OTOC motivated from operator growth. Chaos data from simpler observables?

- Recall that $G^R_{\varepsilon\varepsilon}(\omega, p)$ encodes hydro response. Family of poles

$$\omega_{\text{pole}}(p) = \begin{cases} \pm c_s p + \dots & \text{(sound)} \\ -iDp^2 + \dots & \text{(energy diffusion)} \end{cases}$$

- In low-T SYK can compute away from hydro regime [Gu, Qi, Stanford]

$$G^R_{\varepsilon\varepsilon}(\omega, p) = \frac{s}{\beta} \frac{Dp^2(1+\omega^2)}{-i\omega + Dp^2}$$

At $(\omega, p) = i\lambda_L \, (1, 1/v_B)$ residue of hydro pole vanishes. [Blake, Lee, Liu]

Pole skipping

OTOC motivated from operator growth. Chaos data from simpler observables?

- Recall that $G^R_{\varepsilon\varepsilon}(\omega, p)$ encodes hydro response. Family of poles

$$\omega_{\text{pole}}(p) = \begin{cases} \pm c_s p + \dots & \text{(sound)} \\ -iDp^2 + \dots & \text{(energy diffusion)} \end{cases}$$

- In low-T SYK can compute away from hydro regime [Gu, Qi, Stanford]

$$G^R_{\varepsilon\varepsilon}(\omega, p) = \frac{s}{\beta} \frac{Dp^2(1+\omega^2)}{-i\omega + Dp^2}$$

At $(\omega, p) = i\lambda_L\,(1, 1/v_B)$ residue of hydro pole vanishes. [Blake, Lee, Liu]

- In AdS/CFT at pole skipping point one Einstein eq. trivializes
Green function ambiguous as computed from ratio of two falloffs:

$$G^R_{\varepsilon\varepsilon}(\omega, p) = \frac{b(\omega, p)}{a(\omega, p)}$$

Pole is zero of $a(\omega, p)$, zeros come from $b(\omega, p)$. At p.s. point two indep infalling modes.
[Grozdanov, Schalm, Scopelliti; Blake, Davison, Grozdanov, Liu]

Pole skipping

OTOC motivated from operator growth. Chaos data from simpler observables?

- At $(\omega, p) = i\lambda_L\,(1, 1/v_B)$ residue of hydro pole vanishes.
  Pole skipping is subtle signature of chaos in 2-point function
  [Grozdanov, Schalm, Scopelliti; Blake, Lee, Liu]

Pole skipping

OTOC motivated from operator growth. Chaos data from simpler observables?

- At $(\omega, p) = i\lambda_L\,(1, 1/v_B)$ residue of hydro pole vanishes.
  Pole skipping is subtle signature of chaos in 2-point function
  [Grozdanov, Schalm, Scopelliti; Blake, Lee, Liu]

- Tested for maximally chaotic theories: AdS/CFT, low-T SYK chain, stress tensor dominated CFT in $\mathbb{H}^{d-1} \times S^1$ [Haehl, Reeves, Rozali]

- Predicted by EFT for maximal chaos [Blake, Lee, Liu]

Pole skipping

OTOC motivated from operator growth. Chaos data from simpler observables?

- At $(\omega, p) = i\lambda_L\,(1, 1/v_B)$ residue of hydro pole vanishes.
  Pole skipping is subtle signature of chaos in 2-point function
  [Grozdanov, Schalm, Scopelliti; Blake, Lee, Liu]

- Tested for maximally chaotic theories: AdS/CFT, low-T SYK chain, stress tensor dominated CFT in $\mathbb{H}^{d-1} \times S^1$ [Haehl, Reeves, Rozali]

- Predicted by EFT for maximal chaos [Blake, Lee, Liu]

Non-maximal chaos generalization? [Choi, MM, Sárosi]

- $G^R_{\varepsilon\varepsilon}(\omega, p)$ is universal in CFT in $\mathbb{H}^{d-1} \times S^1$ (including 2d CFT at finite T), but not all of these are maximally chaotic. Also, $v_B < v_B^{(T)}$ at weak coupling.

Pole skipping

OTOC motivated from operator growth. Chaos data from simpler observables?

- At $(\omega, p) = i\lambda_L\,(1, 1/v_B)$ residue of hydro pole vanishes.
  Pole skipping is subtle signature of chaos in 2-point function
  [Grozdanov, Schalm, Scopelliti; Blake, Lee, Liu]

- Tested for maximally chaotic theories: AdS/CFT, low-T SYK chain, stress tensor dominated CFT in $\mathbb{H}^{d-1} \times S^1$ [Haehl, Reeves, Rozali]

- Predicted by EFT for maximal chaos [Blake, Lee, Liu]

Non-maximal chaos generalization? [Choi, MM, Sárosi]

- $G^R_{\varepsilon\varepsilon}(\omega, p)$ is universal in CFT in $\mathbb{H}^{d-1} \times S^1$ (including 2d CFT at finite T), but not all of these are maximally chaotic. Also, $v_B < v_B^{(T)}$ at weak coupling.

- Proposal: $(\omega, p)_{\text{p.s.}} = i\dfrac{2\pi}{\beta}\left(1, \dfrac{1}{v_B^{(T)}}\right)$

Pole skipping

Proposal: $$\boxed{(\omega, p)_{\text{p.s.}} = i\frac{2\pi}{\beta}\left(1, \frac{1}{v_B^{(T)}}\right)}$$

Test in large q SYK chain [Choi, MM, Sárosi]

1. $G^R_{\varepsilon\varepsilon}(\omega, p)$ extracted from OPE limit of four point function, i.e. $\langle \delta g_x(\tau_1, \tau_2)\, \delta g_y(\tau_3, \tau_4)\rangle$ of the bilocal action

$$S_{\text{eff}} = \frac{N}{4q^2}\sum_x \int d\tau_1 d\tau_2 \, \left[\frac{1}{4}\partial_1 g_x \partial_2 g_x - \mathcal{J}_0^2 e^{g_x} - \mathcal{J}_1^2 e^{\frac{1}{2}(g_x + g_{x+1})}\right]$$

Pole skipping

Proposal: $$\boxed{(\omega, p)_{\text{p.s.}} = i\frac{2\pi}{\beta}\left(1, \frac{1}{v_B^{(T)}}\right)}$$

Test in large q SYK chain [Choi, MM, Sárosi]

1. $G^R_{\varepsilon\varepsilon}(\omega, p)$ extracted from OPE limit of four point function, i.e. $\langle \delta g_x(\tau_1, \tau_2)\, \delta g_y(\tau_3, \tau_4)\rangle$ of the bilocal action
$$S_{\text{eff}} = \frac{N}{4q^2}\sum_x \int d\tau_1 d\tau_2 \left[\frac{1}{4}\partial_1 g_x \partial_2 g_x - \mathcal{J}_0^2 e^{g_x} - \mathcal{J}_1^2 e^{\frac{1}{2}(g_x + g_{x+1})}\right]$$
2. Linearize around saddle: $\left[-\partial_\theta^2 + \frac{h(h-1)}{\sin^2(\theta)}\right]\psi_n = \left(\frac{n}{g}\right)^2 \psi_n$
$$\psi_n^e = \sin^h\theta\, {}_2F_1\left(\frac{h-n/g}{2}, \frac{h+n/g}{2}, \frac{1}{2}; \cos^2\theta\right)$$
$$\psi_n^o = \cos\theta \sin^h\theta\, {}_2F_1\left(\frac{1+h-n/g}{2}, \frac{1+h+n/g}{2}, \frac{3}{2}; \cos^2\theta\right)$$

Pole skipping

Proposal: $$\boxed{(\omega, p)_{\text{p.s.}} = i\frac{2\pi}{\beta}\left(1, \frac{1}{v_B^{(T)}}\right)}$$

Test in large q SYK chain [Choi, MM, Sárosi]

1. $G^R_{\varepsilon\varepsilon}(\omega, p)$ extracted from OPE limit of four point function, i.e. $\langle \delta g_x(\tau_1, \tau_2)\, \delta g_y(\tau_3, \tau_4)\rangle$ of the bilocal action
$$S_{\text{eff}} = \frac{N}{4q^2}\sum_x \int d\tau_1 d\tau_2 \left[\frac{1}{4}\partial_1 g_x \partial_2 g_x - \mathcal{J}_0^2 e^{g_x} - \mathcal{J}_1^2 e^{\frac{1}{2}(g_x + g_{x+1})}\right]$$
2. Linearize around saddle: $\left[-\partial_\theta^2 + \frac{h(h-1)}{\sin^2(\theta)}\right]\psi_n = \left(\frac{n}{g}\right)^2 \psi_n$
$$\psi_n^e = \sin^h\theta\, {}_2F_1\left(\frac{h - n/g}{2}, \frac{h+n/g}{2}, \frac{1}{2}; \cos^2\theta\right)$$
$$\psi_n^o = \cos\theta \sin^h\theta\, {}_2F_1\left(\frac{1 + h - n/g}{2}, \frac{1+h+n/g}{2}, \frac{3}{2}; \cos^2\theta\right)$$
3. Matsubara Green's function
$$G^M_{\varepsilon\varepsilon}(n, p) \propto \begin{cases} -\partial_\theta \log \psi_n^e(\theta_g) & n \in 2\mathbb{Z} \\ -\partial_\theta \log \psi_n^o(\theta_g) & n \in 2\mathbb{Z}+1 \end{cases}$$

Pole skipping

Proposal: $$\boxed{(\omega, p)_{\text{p.s.}} = i\frac{2\pi}{\beta}\left(1, \frac{1}{v_B^{(T)}}\right)}$$

Test in large q SYK chain [Choi, MM, Sárosi]

1. $G^R_{\varepsilon\varepsilon}(\omega, p)$ extracted from OPE limit of four point function, i.e. $\langle \delta g_x(\tau_1, \tau_2)\, \delta g_y(\tau_3, \tau_4)\rangle$ of the bilocal action

$$S_{\text{eff}} = \frac{N}{4q^2}\sum_x \int d\tau_1 d\tau_2 \left[\frac{1}{4}\partial_1 g_x \partial_2 g_x - \mathcal{J}_0^2 e^{g_x} - \mathcal{J}_1^2 e^{\frac{1}{2}(g_x + g_{x+1})}\right]$$

2. Linearize around saddle: $\left[-\partial_\theta^2 + \frac{h(h-1)}{\sin^2(\theta)}\right]\psi_n = \left(\frac{n}{g}\right)^2 \psi_n$

$$\psi_n^e = \sin^h\theta\, {}_2F_1\left(\frac{h-n/g}{2}, \frac{h+n/g}{2}, \frac{1}{2}; \cos^2\theta\right)$$

$$\psi_n^o = \cos\theta \sin^h\theta\, {}_2F_1\left(\frac{1+h-n/g}{2}, \frac{1+h+n/g}{2}, \frac{3}{2}; \cos^2\theta\right)$$

3. Matsubara Green's function

$$G^M_{\varepsilon\varepsilon}(n, p) \propto \begin{cases} -\partial_\theta \log \psi_n^e(\theta_g) & n \in 2\mathbb{Z} \\ -\partial_\theta \log \psi_n^o(\theta_g) & n \in 2\mathbb{Z}+1 \end{cases}$$

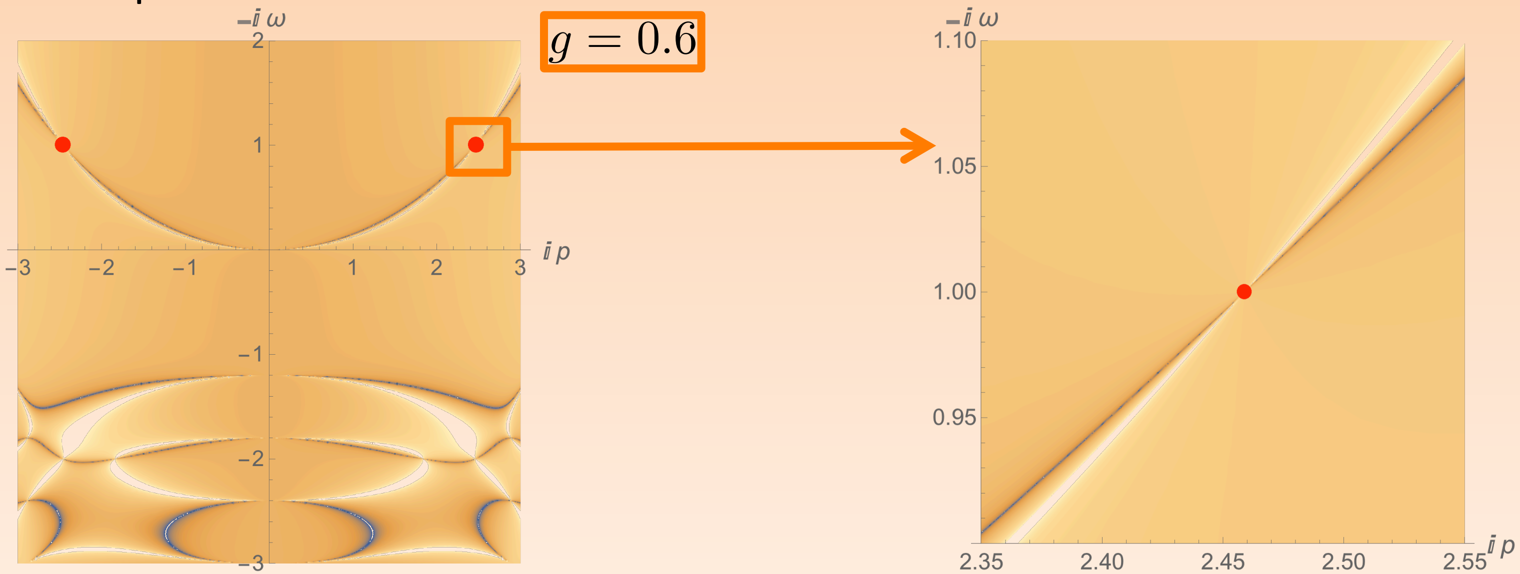
4. Find unique analytic continuation

$$G^R_{\varepsilon\varepsilon}(\omega, p) \propto -\partial_\theta \log \psi_n(\theta_g)\Big|_{n \to -i\omega+\epsilon}, \qquad \psi_n(\theta) \equiv c_e \psi_n^e + c_o \psi_n^o$$

Pole skipping

- Test in large q SYK chain

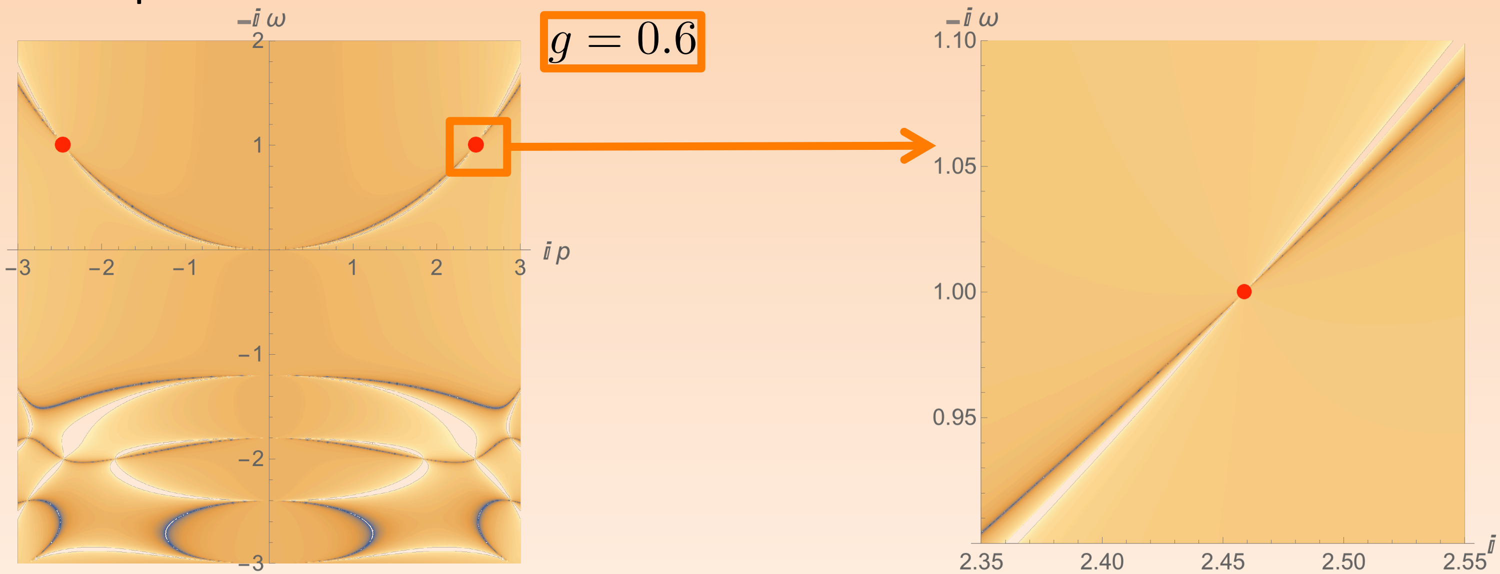
    5. Trace pole and zero lines



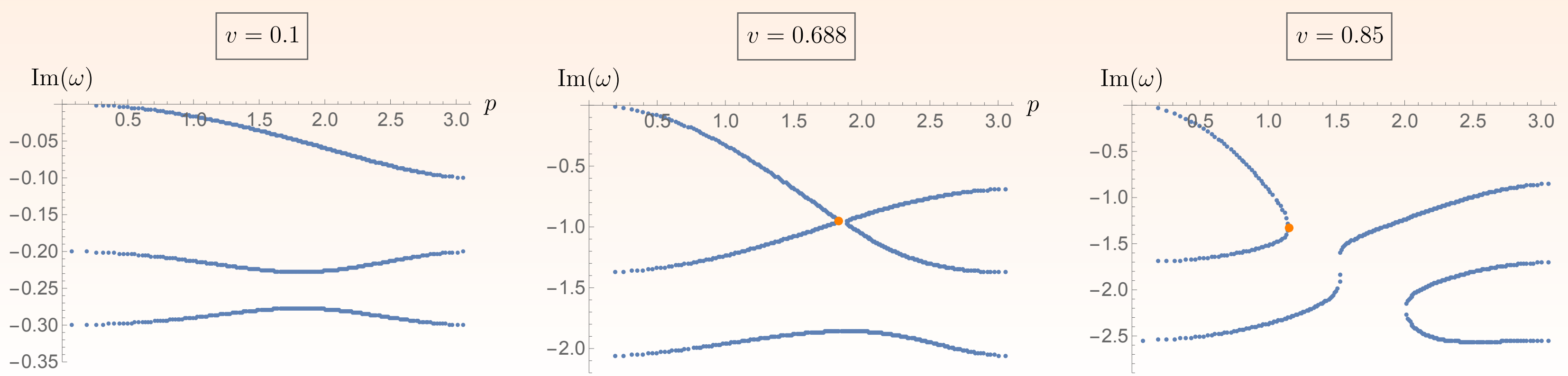
Pole skipping

- Test in large q SYK chain

  5. Trace pole and zero lines



  6. Can also analyze dispersion relations to all orders in the derivative expansion [Withers; Grozdanov, Kovtun, Starinets, Tadic]



Closed form thermal Green function

Nabil Iqbal
@nblqbl

This paper today is brilliant: arxiv.org/pdf/2010.08558.... One of the most remarkable things is their derivation (in a convenient model) of an expression for a energy-energy finite-temperature correlator at *all values of the coupling*. 1/3

the simple formula:

$$\boxed{G^R_{\varepsilon\varepsilon}(\omega) = -\frac{Nv}{2q^2}\left(\partial_\theta \log \psi_n(\theta_v) + \tan\frac{\pi v}{2}\frac{h(h-1)}{2}\right)\Big|_{n\to -i\omega+\epsilon},} \qquad (1.8)$$

where v is the SYK coupling constant, we chose the inverse temperature $\beta = 2\pi$ (without

6:11 PM · Oct 20, 2020 · Twitter Web App

5 Likes

Nabil Iqbal @nblqbl · Oct 20
Replying to @nblqbl
When interactions are important such a correlator should be controlled by hydrodynamics; this expression lets us see explicitly how things like the diffusion pole etc. emerge from field-theoretical soup as we change the coupling. 2/3

1

Nabil Iqbal @nblqbl · Oct 20
As far as I know, this is the only expression of its kind -- we usually are stuck at weak coupling, or *extremely* strong coupling if we use holography. Very happy to learn that we can interpolate between the two even in this dirty finite-T setting. 3/3

Closed form thermal Green function

Nabil Iqbal
@nblqbl

This paper today is brilliant: arxiv.org/pdf/2010.08558.... One of the most remarkable things is their derivation (in a convenient model) of an expression for a energy-energy finite-temperature correlator at *all values of the coupling*. 1/3

the s

wher

6:11 P

5 Lik

Nabil Iqbal @nblqbl · Oct 20

As far as I know, this is the only expression of its kind -- we usually are stuck at weak coupling, or *extremely* strong coupling if we use holography. Very happy to learn that we can interpolate between the two even in this dirty finite-T setting. 3/3

When interactions are important such a correlator should be controlled by hydrodynamics; this expression lets us see explicitly how things like the diffusion pole etc. emerge from field-theoretical soup as we change the coupling. 2/3

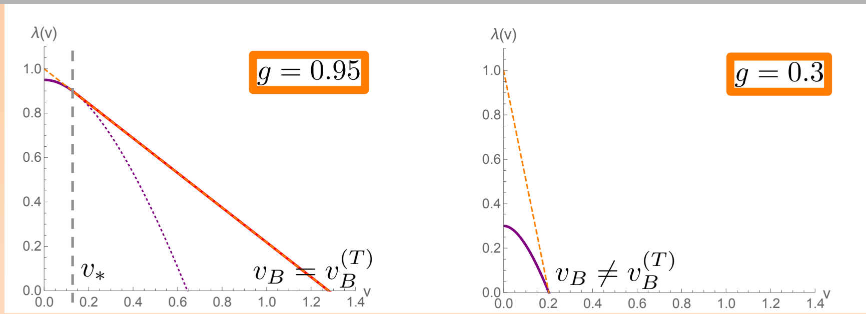
1

Nabil Iqbal @nblqbl · Oct 20

As far as I know, this is the only expression of its kind -- we usually are stuck at weak coupling, or *extremely* strong coupling if we use holography. Very happy to learn that we can interpolate between the two even in this dirty finite-T setting. 3/3

Summary

Spatial structure of OTOC is probed by $\lambda(v)$

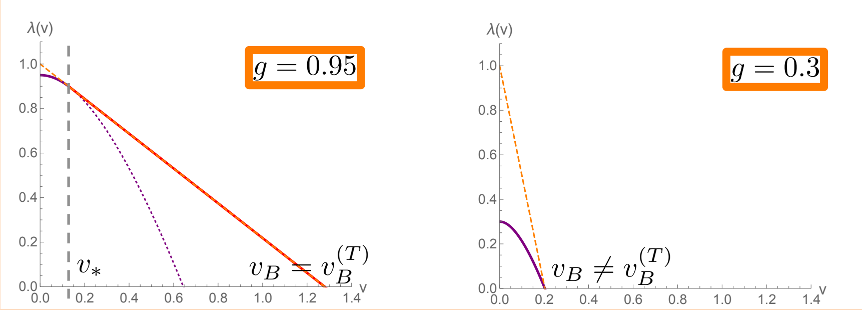


$$C(t, x = vt) = \frac{\#}{N^2}\,\exp\left(\lambda(v)\,t\right) + \ldots$$

$$\lambda(v) \leq \frac{2\pi}{\beta}\left(1 - \frac{|v|}{v_B}\right)$$

- Explicit examples in AdS/CFT, SYK chains, CFTs in $\mathbb{H}^{d-1} \times S^1$, …
  Refined chaos bound is saturated, when stress tensor dominates.

Summary



Spatial structure of OTOC is probed by $\lambda(v)$

$$C(t, x = vt) = \frac{\#}{N^2} \exp\left(\lambda(v)\, t\right) + \dots$$

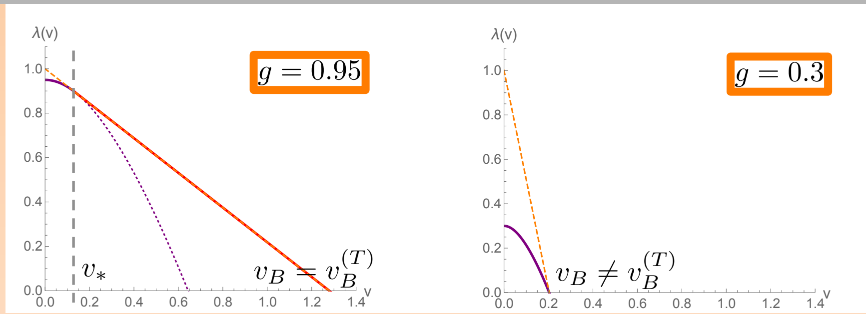
$$\lambda(v) \leq \frac{2\pi}{\beta}\left(1 - \frac{|v|}{v_B}\right)$$

- Explicit examples in AdS/CFT, SYK chains, CFTs in $\mathbb{H}^{d-1} \times S^1$, …
  Refined chaos bound is saturated, when stress tensor dominates.

Pole skipping happens at $(\omega, p)_{\text{p.s.}} = i\frac{2\pi}{\beta}\left(1, \frac{1}{v_B^{(T)}}\right)$

- Captures stress tensor contribution to chaos, for $v_* \leq v \leq v_B$ chaos is controlled by it.
  (This contribution can be decreased or cancelled completely.)

Summary



Spatial structure of OTOC is probed by $\lambda(v)$

$$C(t, x = vt) = \frac{\#}{N^2} \exp\left(\lambda(v)\, t\right) + \dots$$

$$\lambda(v) \leq \frac{2\pi}{\beta}\left(1 - \frac{|v|}{v_B}\right)$$

- Explicit examples in AdS/CFT, SYK chains, CFTs in $\mathbb{H}^{d-1} \times S^1$, …
  Refined chaos bound is saturated, when stress tensor dominates.

Pole skipping happens at $(\omega, p)_{\text{p.s.}} = i\frac{2\pi}{\beta}\left(1, \frac{1}{v_B^{(T)}}\right)$

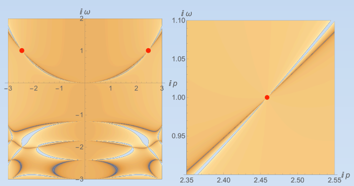
- Captures stress tensor contribution to chaos, for $v_* \leq v \leq v_B$ chaos is controlled by it.
  (This contribution can be decreased or cancelled completely.)

- Demystifies pole skipping: $G^R_{\varepsilon\varepsilon}(\omega, p)$ and $v_B^{(T)}$ both are properties of the stress tensor, stress tensor does not know about λ_L

- Closed form thermal Green function

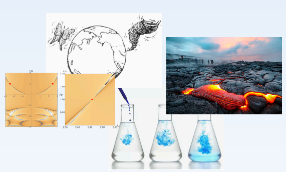
Outline

Butterfly effect
- Butterfly effect, operator growth and OTOC
- Refinement of the chaos bound



Pole skipping
- Away from maximal chaos
- Explicit thermal Green's function

Thermalization
- Entanglement entropy as a probe
- Membrane theory is the EFT



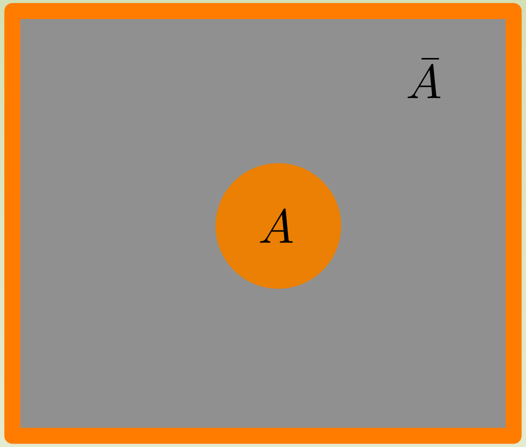
Summary and open questions

Thermalization through the lens of EE

Quantum thermalization

- To define thermalization we need coarse graining

  In a gas, we coarse grain multi-particle correlations.
  In many body systems or QFTs consider subsystems
  $\rho_A = \mathrm{Tr}_{\bar{A}} \, |\psi\rangle \langle\psi|$



Thermalization through the lens of EE

Quantum thermalization

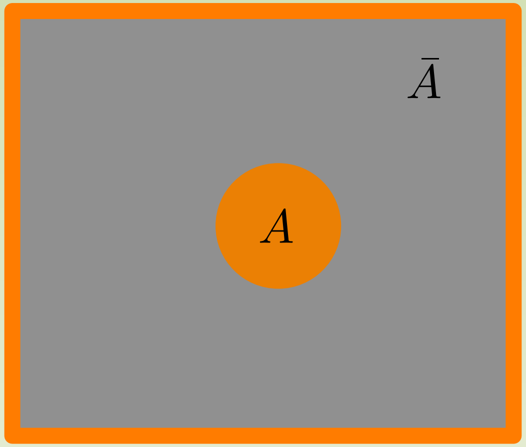
- To define thermalization we need coarse graining

  In a gas, we coarse grain multi-particle correlations.
  In many body systems or QFTs consider subsystems
  $\rho_A = \mathrm{Tr}_{\bar{A}} \, |\psi\rangle \langle\psi|$

- In analogy with the Second Law, expect the EE

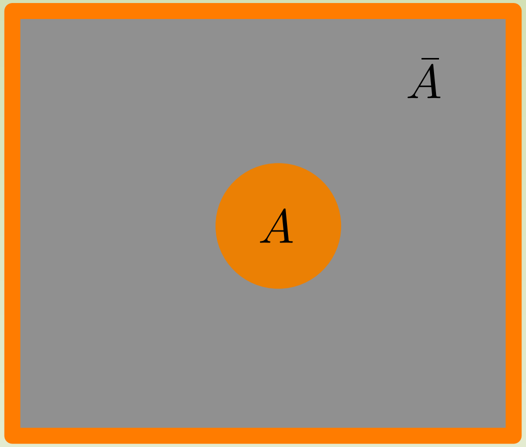
  $$S_A = -\mathrm{Tr}\left(\rho_A \log \rho_A\right)$$

  to increase with time.



Thermalization through the lens of EE

Quantum thermalization



- To define thermalization we need coarse graining

  In a gas, we coarse grain multi-particle correlations.
  In many body systems or QFTs consider subsystems

  $$\rho_A = \mathrm{Tr}_{\bar{A}}\, |\psi\rangle\langle\psi|$$

- In analogy with the Second Law, expect the EE

  $$S_A = -\mathrm{Tr}\left(\rho_A \log \rho_A\right)$$

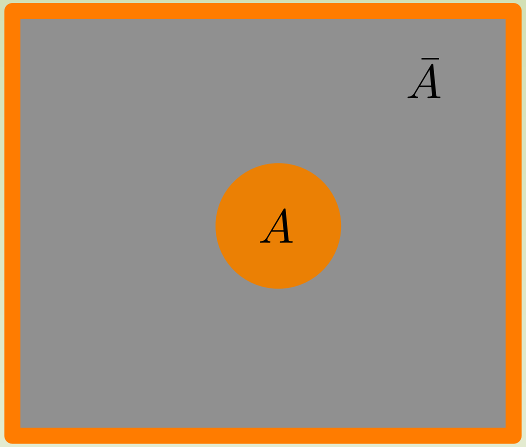
  to increase with time.

- Quench: sparsely entangled initial state, evolves into typical state

  $$\rho_A(t) \;\to\; \rho_A^{(\mathrm{eq})}(\beta) = \mathrm{Tr}_{\bar{A}}\, \frac{e^{-\beta H}}{Z}$$

Thermalization through the lens of EE

Quantum thermalization



- To define thermalization we need coarse graining

  In a gas, we coarse grain multi-particle correlations.
  In many body systems or QFTs consider subsystems

  $$\rho_A = \mathrm{Tr}_{\bar{A}} \, |\psi\rangle \langle\psi|$$

- In analogy with the Second Law, expect the EE

  $$S_A = -\mathrm{Tr}\left(\rho_A \log \rho_A\right)$$

  to increase with time.

- Quench: sparsely entangled initial state, evolves into typical state

  $$\rho_A(t) \;\to\; \rho_A^{(\mathrm{eq})}(\beta) = \mathrm{Tr}_{\bar{A}} \, \frac{e^{-\beta H}}{Z}$$

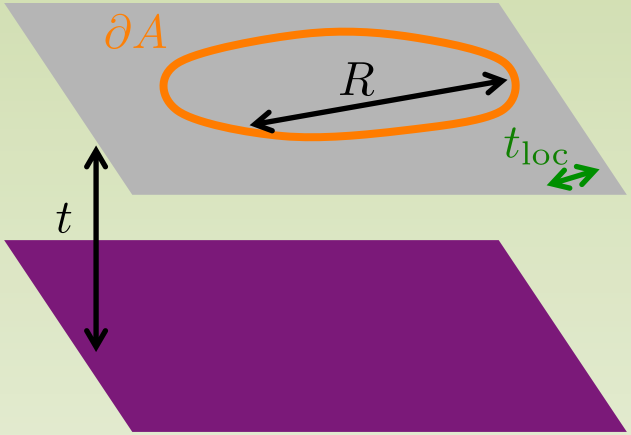
- Instead of following an operator (matrix), we follow a number

  $$S_A(t) \;\to\; S_A^{(\mathrm{eq})}(\beta) = s_{\mathrm{th}}(\beta)\,\mathrm{vol}(A)$$

  Universal probe, captures the essence of thermalization

Entropy in the hydrodynamic limit

Thermalization in quantum quenches



- Evolution of conserved densities universal in hydro limit

  $$\frac{t}{R} = \text{fixed}\,, \qquad R, t \gg t_{\mathrm{loc}} \sim \beta$$

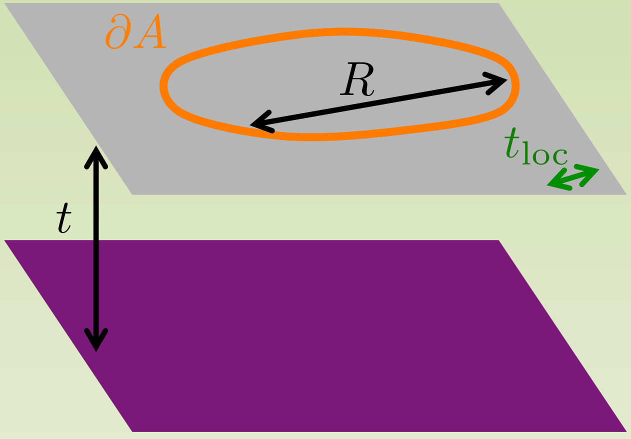
  EE dynamics expected to simplify in the same limit

  Goal: develop effective theory for extensive piece

  $$S(t) = s_{\mathrm{th}} R^{d-1} \mathcal{S}_{\mathrm{ext}}\left(\frac{t}{R}\right) + \ldots$$

Entropy in the hydrodynamic limit

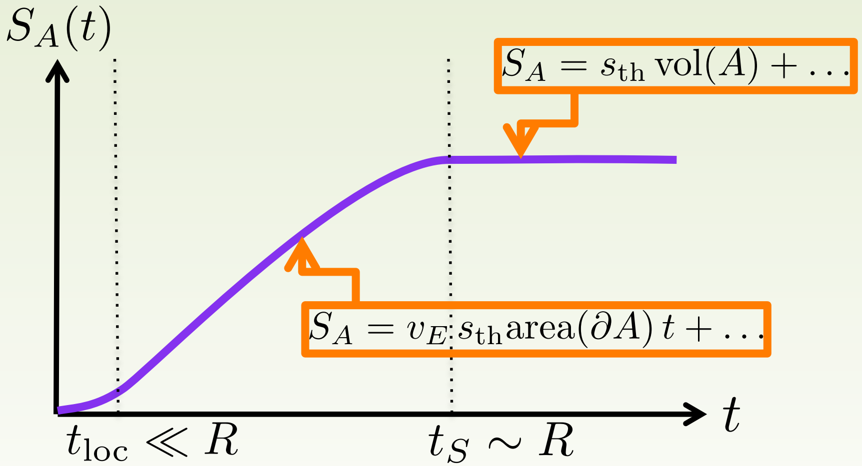
Thermalization in quantum quenches



- Evolution of conserved densities universal in hydro limit
  $$\frac{t}{R} = \text{fixed}\,, \qquad R, t \gg t_{\rm loc} \sim \beta$$
  EE dynamics expected to simplify in the same limit
  Goal: develop effective theory for extensive piece
  $$S(t) = s_{\rm th} R^{d-1} \mathcal{S}_{\rm ext}\left(\frac{t}{R}\right) + \dots$$

- Qualitative picture of EE from 2d CFT [Cardy, Calabrese], AdS/CFT [Hartman, Maldacena; Liu, Suh], free theory in higher d [Casini, Liu, MM; Cotler, Hertzberg, MM, Mueller]

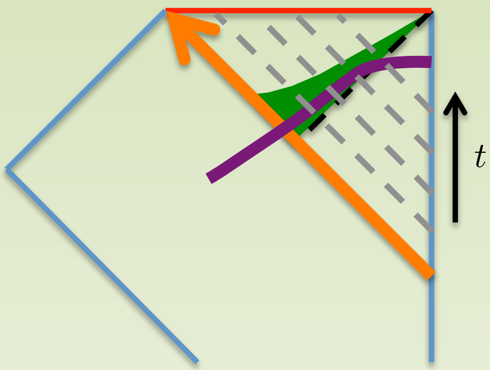
- Increase of EE in itself does not detect chaos, but its detailed dynamics is universal and differs from integrable theories



Membrane theory of entanglement dynamics

The membrane theory can be derived in two disparate physical systems

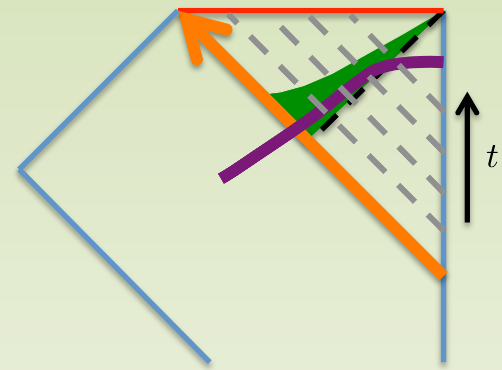
- In AdS/CFT EE is computed by extremal surface area probing the out of equilibrium state [Hubeny, Rangamani, Ryu, Takayanagi]
- Important variables in the hydro limit is the HRT surface projection to the **boundary spacetime** [MM_2]



Membrane theory of entanglement dynamics

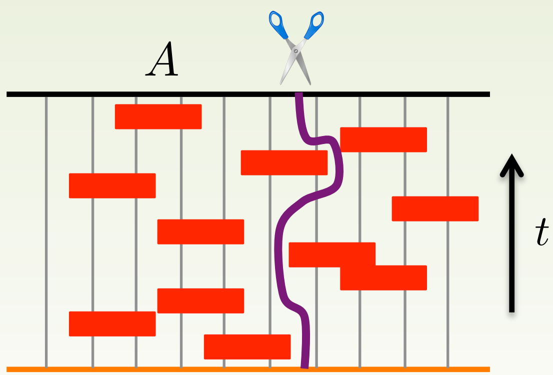
The membrane theory can be derived in two disparate physical systems

- In AdS/CFT EE is computed by extremal surface area probing the out of equilibrium state [Hubeny, Rangamani, Ryu, Takayanagi]



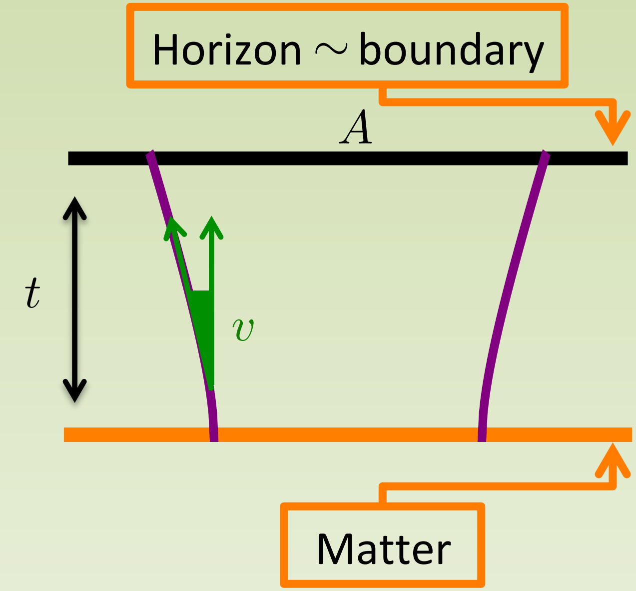
- Important variables in the hydro limit is the HRT surface projection to the **boundary spacetime** [MM_2]

- In random quantum circuit models of time evolution, EE upper bound by minimal cut is saturated in hydro limit [Nahum, Ruhman, Vijay, Haah; Jonay, Huse, Nahum]



- Remarkable unification of CMT and HEP approaches

Membrane theory of entanglement dynamics



- Dynamics of projection governed by local action

$$S[A(t)] = s_{\mathrm{th}} \int_0^t dt' \; \mathcal{E}\,(v)$$

with membrane ending on A on upper boundary, perpendicularly on lower boundary.

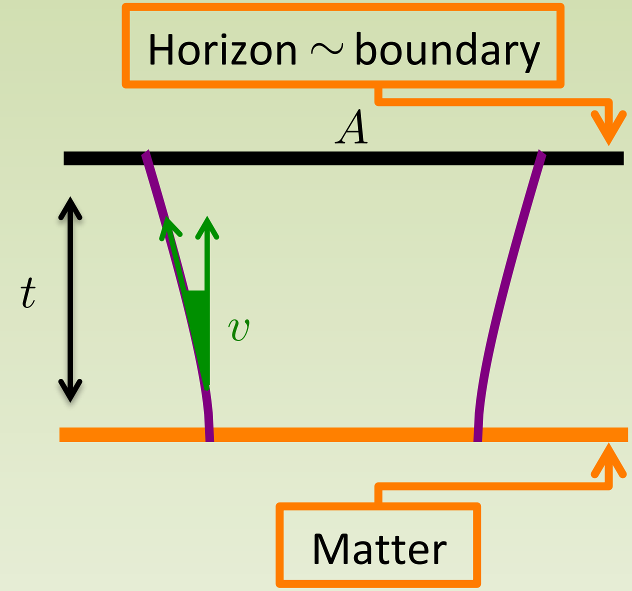
- Minimal membrane action computes entropy. $\mathcal{E}(v)$ is repackaging of geometry, independent of quench details.

Membrane theory of entanglement dynamics

- Dynamics of projection governed by local action

$$S[A(t)] = s_{\mathrm{th}} \int_0^t dt' \; \mathcal{E}\left(v\right)$$

with membrane ending on A on upper boundary, perpendicularly on lower boundary.

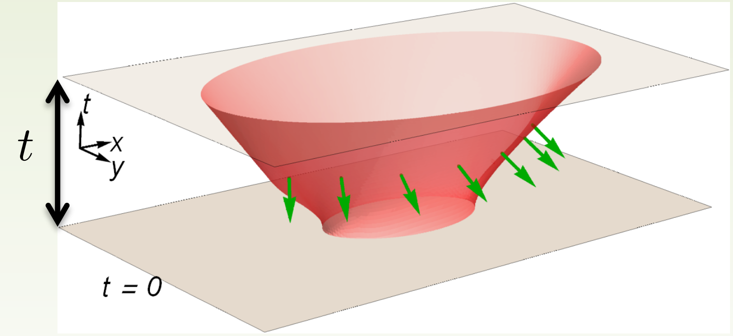


- Minimal membrane action computes entropy. $\mathcal{E}(v)$ is repackaging of geometry, independent of quench details.

- In higher dim. get true membrane

$$S[A] = s_{\mathrm{th}} \int d^{d-1}\xi \; \sqrt{|\gamma|} \, \frac{\mathcal{E}\left(v\right)}{\sqrt{1-v^2}}$$

[MM, van der Schee]



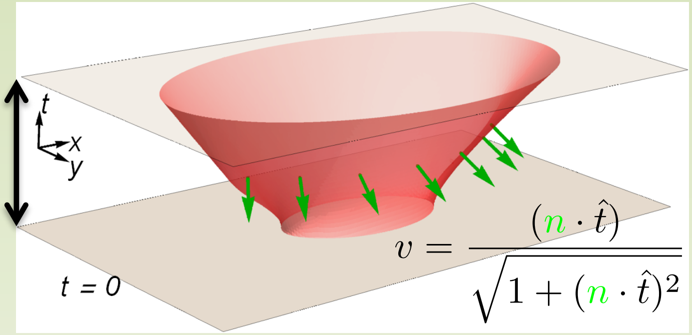
$$v = \frac{(n \cdot \hat{t})}{\sqrt{1+(n\cdot\hat{t})^2}}$$

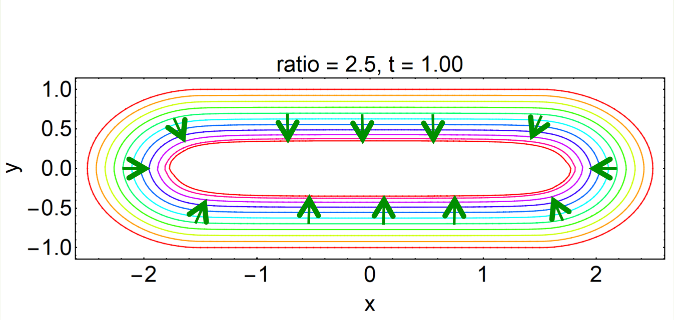
Membrane theory of entanglement dynamics

Can reformulate holographic surface extremization in d+1 dimensions as membrane minimization in d dimensions in the limit hydro limit. [MM$_2$]

- Membrane theory:

$$S[A] = s_{\text{th}} \int d^{d-1}\xi \ \sqrt{|\gamma|}\, \frac{\mathcal{E}(v)}{\sqrt{1-v^2}}$$





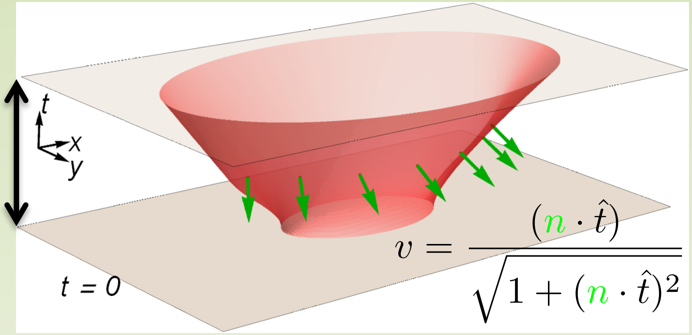
Membrane theory of entanglement dynamics

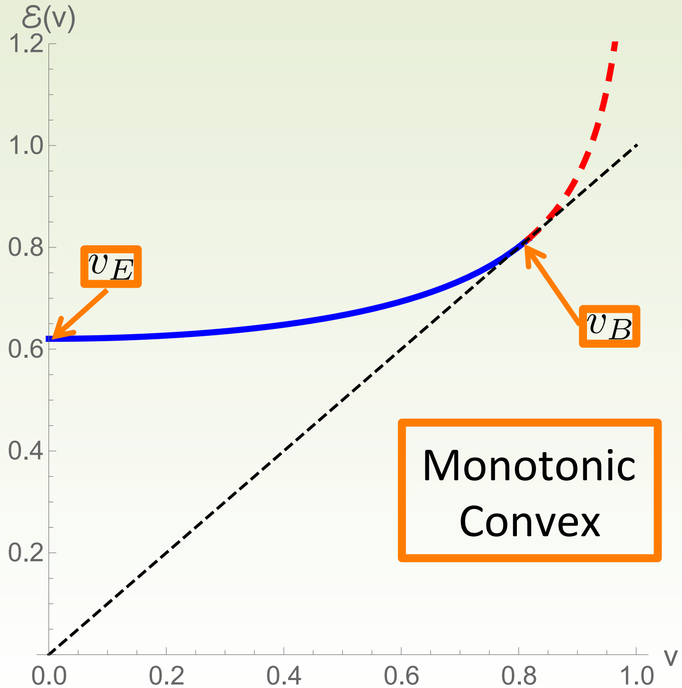
Can reformulate holographic surface extremization in d+1 dimensions as membrane minimization in d dimensions in the limit hydro limit. [MM_2]

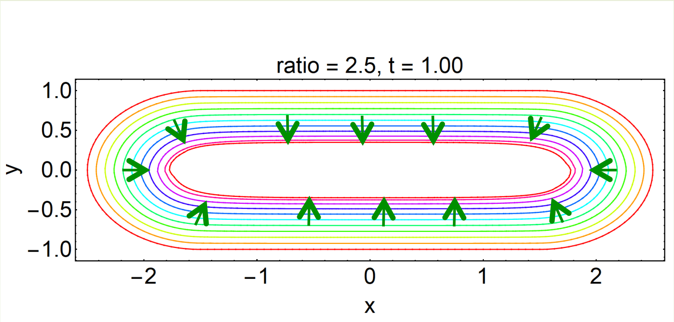
- Membrane theory:

$$S[A] = s_{\text{th}} \int d^{d-1}\xi \;\sqrt{|\gamma|}\; \frac{\mathcal{E}\left(v\right)}{\sqrt{1-v^2}}$$

- Using the NEC, can prove the following properties of $\mathcal{E}(v)$, can be thought of as a transport coeff.



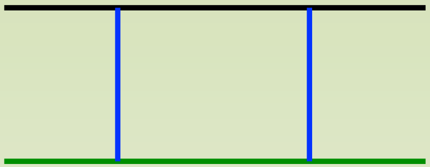


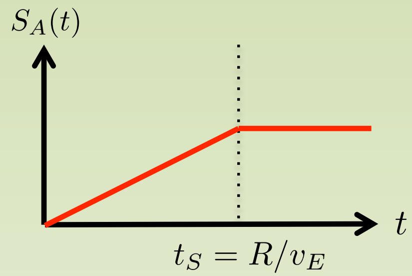


Applications

EE for strip, sphere, cylinder regions in the hydro limit is analytically solvable. [MM_1; MM_2]

- Strip:

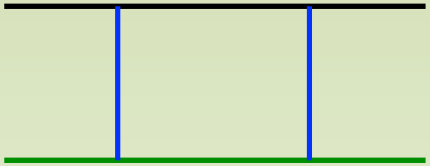


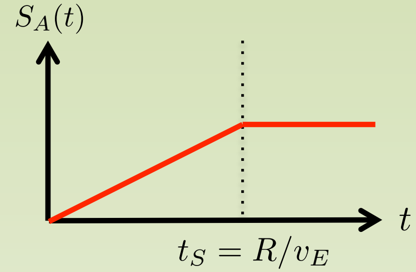


Applications

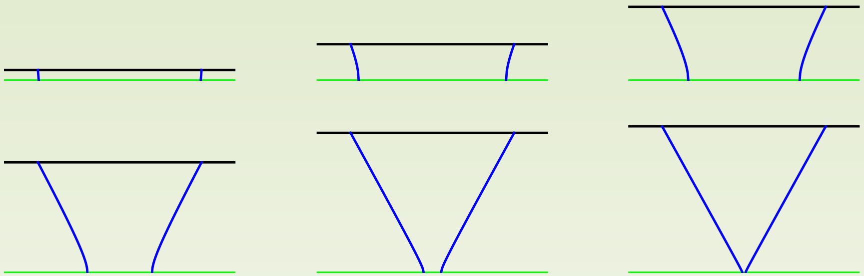
EE for strip, sphere, cylinder regions in the hydro limit is analytically solvable. [MM$_1$; MM$_2$]

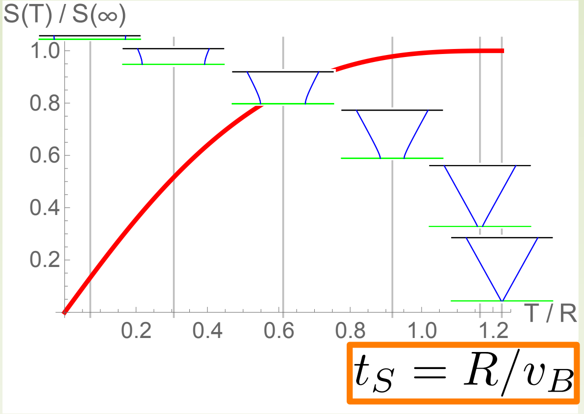
- Strip:





- Sphere:

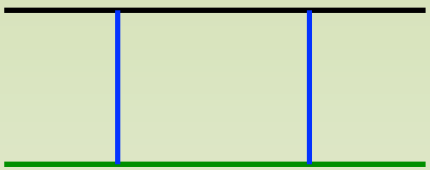


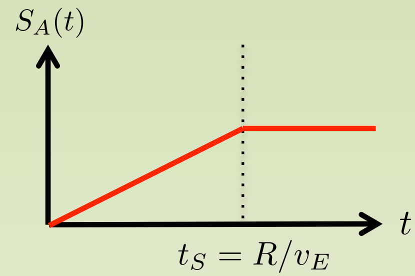


Applications

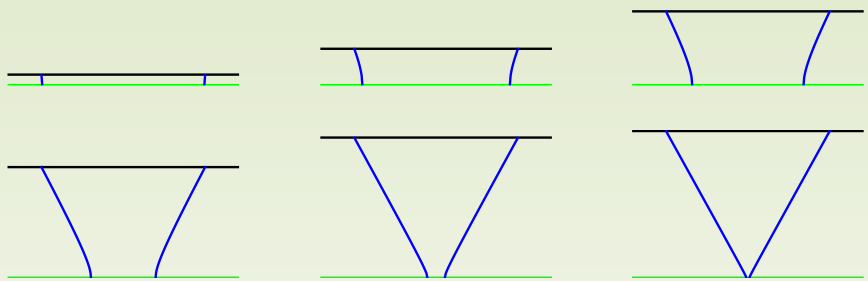
EE for strip, sphere, cylinder regions in the hydro limit is analytically solvable. [MM$_1$; MM$_2$]

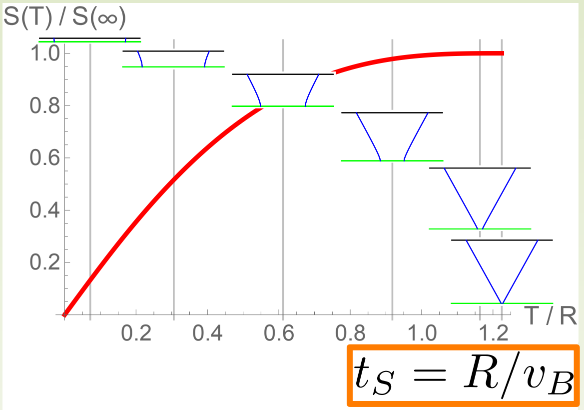
- Strip:





- Sphere:





- Simple bound on saturation time from operator growth: [MM, Stanford] $t_S \geq R/v_B$

For elongated shapes in 4D we find: [MM, van der Schee] $\boxed{t_S = R/v_B}$

Black holes (often) saturate entanglement entropy the fastest.

Extensions

The membrane theory is robust, can be generalized away from global quenches [MM, Virrueta]

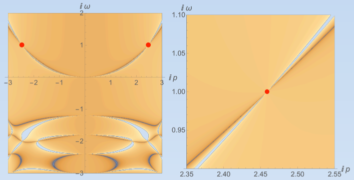
- Fluid/gravity black brane dual to an inhomogenous state in local thermal equilibrium. To subleading order, we get the membrane coupled to hydrodynamics:

$$S = \int d^{d-1}\xi \, \sqrt{|\gamma|}\, s_{\rm th}(x) \frac{\mathcal{E}(v)}{\sqrt{1-v^2}} + \dots , \qquad v(x) \equiv \frac{(n \cdot u(x))}{\sqrt{1 + (n \cdot u(x))^2}}$$

- **Membrane theory is versatile, has connections to operator growth and hydrodynamics, and has all the features to be a universal theory**

Outline

Butterfly effect
- Butterfly effect, operator growth and OTOC
- Refinement of the chaos bound

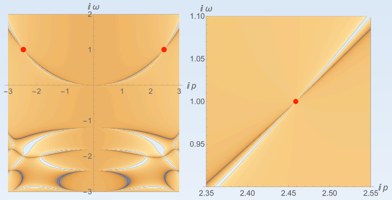


Pole skipping
- Away from maximal chaos
- Explicit thermal Green's function

Thermalization
- Entanglement entropy as a probe
- Membrane theory is the EFT

Summary and open questions

Summary



Phenomena associated with chaotic dynamics:

- Hydrodynamics is the EFT for transport
  Interplays: pole skipping point is continuation of hydro mode
  membrane couples to hydro dofs geometrically

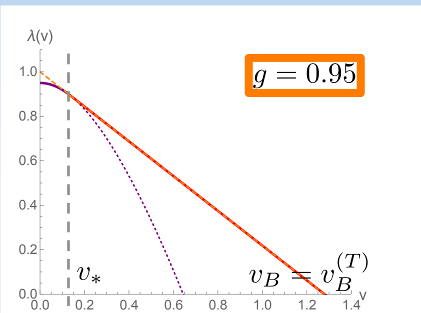
Summary

Phenomena associated with chaotic dynamics:

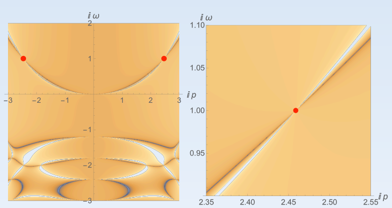
- Hydrodynamics is the EFT for transport
  Interplays: pole skipping point is continuation of hydro mode
  membrane couples to hydro dofs geometrically

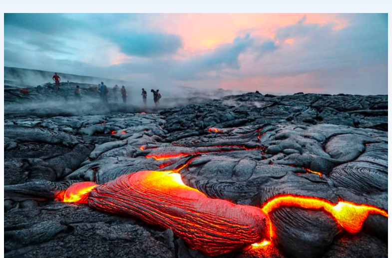
- $\lambda(v)$ characterizes OTOCs,
  refined bound, explicit examples

$$\lambda(v) \leq \frac{2\pi}{\beta}\left(1 - \frac{|v|}{v_B}\right)$$



  EFT from reparametrizations





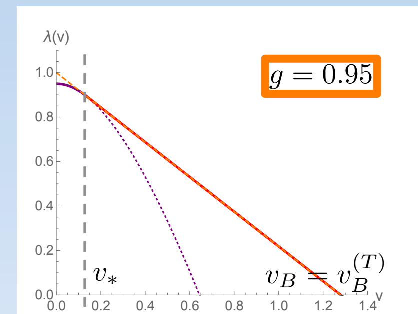
Summary

Phenomena associated with chaotic dynamics:

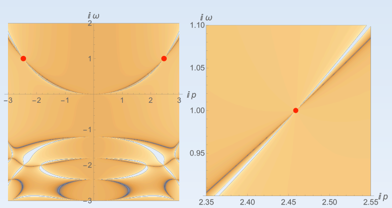
- Hydrodynamics is the EFT for transport
  Interplays: pole skipping point is continuation of hydro mode
  membrane couples to hydro dofs geometrically

- $\lambda(v)$ characterizes OTOCs,
  refined bound, explicit examples

$$\lambda(v) \leq \frac{2\pi}{\beta}\left(1 - \frac{|v|}{v_B}\right)$$

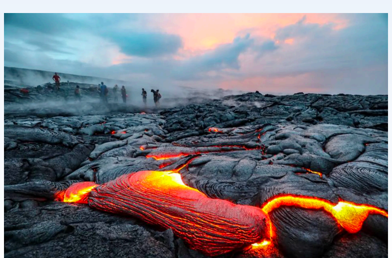


  EFT from reparametrizations



- Demystified pole skipping, explicit thermal Green fn

$$(\omega, p)_{\text{p.s.}} = i\frac{2\pi}{\beta}\left(1, \frac{1}{v_B^{(T)}}\right)$$

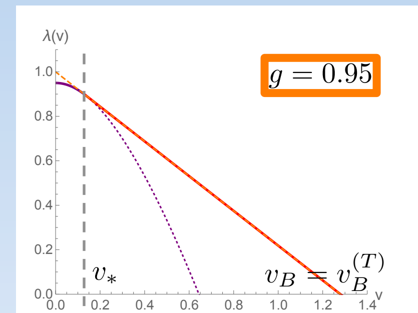


Summary

Phenomena associated with chaotic dynamics:

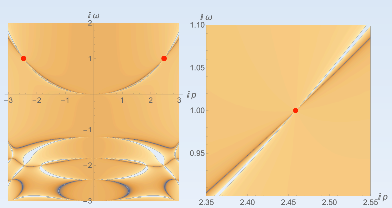
- Hydrodynamics is the EFT for transport
  Interplays: pole skipping point is continuation of hydro mode
  membrane couples to hydro dofs geometrically

- $\lambda(v)$ characterizes OTOCs,
  refined bound, explicit examples



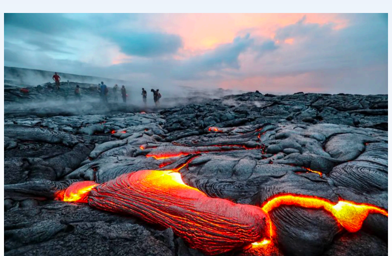
$$\lambda(v) \leq \frac{2\pi}{\beta}\left(1 - \frac{|v|}{v_B}\right)$$

EFT from reparametrizations

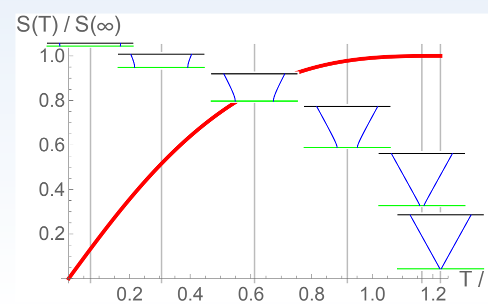


- Demystified pole skipping, explicit thermal Green fn

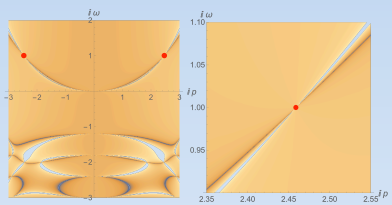
$$(\omega, p)_{\text{p.s.}} = i\frac{2\pi}{\beta}\left(1, \frac{1}{v_B^{(T)}}\right)$$



- Membrane theory of EE dynamics from holography and random circuits, rich applications

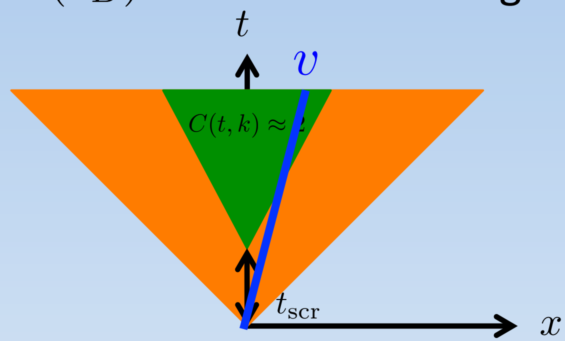


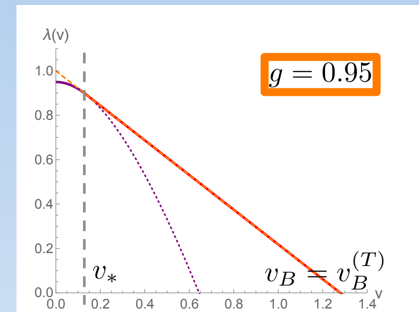
Role of v_B



v_B hints at nontrivial interplay between these phenomena:

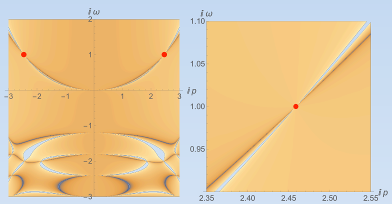
- $\lambda(v_B) = 0$ delineates region in which OTOC grows





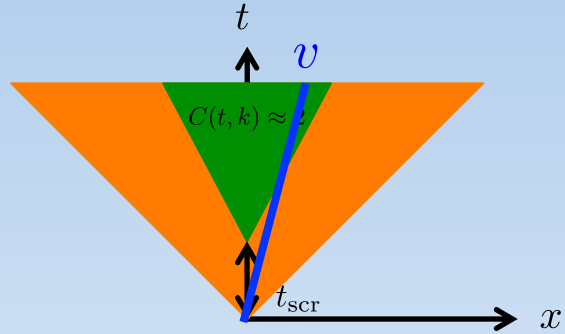
Since for $v_* \leq v \leq v_B = v_B^{(T)}$ stress tensor dominates chaos, reasonable that $G^R_{\varepsilon\varepsilon}$ knows about $v_B^{(T)}$ through pole skipping.

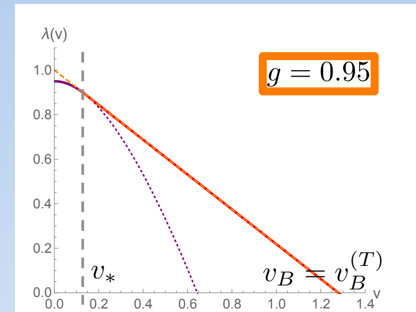
Role of v_B



v_B hints at nontrivial interplay between these phenomena:

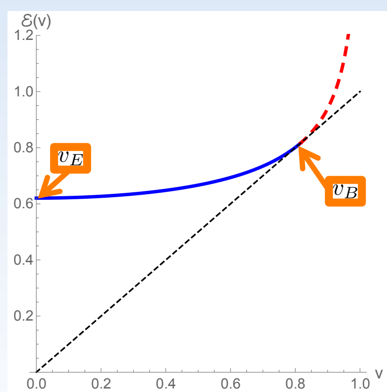
- $\lambda(v_B) = 0$ delineates region in which OTOC grows

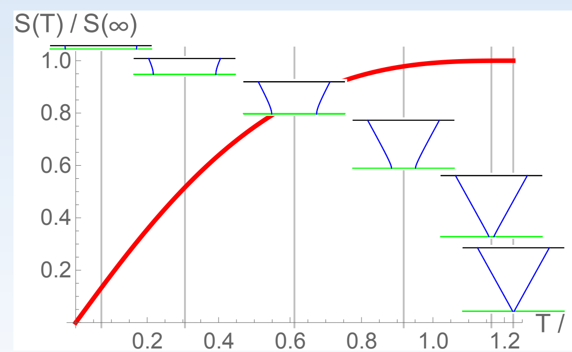




Since for $v_* \leq v \leq v_B = v_B^{(T)}$ stress tensor dominates chaos, reasonable that $G^R_{\varepsilon\varepsilon}$ knows about $v_B^{(T)}$ through pole skipping.

- Manifestations of v_B in EE dynamics





$\boxed{t_S = R/v_B}$

Open questions

Open questions and some hints

- EFT for operator growth? Relation to Schwarzian, Reggeon field theory?
  Hint: Explicit large q SYK results should help in generalizations
  [Choi, Haehl, MM, Sárosi, Streicher wip]

Open questions

Open questions and some hints

- EFT for operator growth? Relation to Schwarzian, Reggeon field theory?
  Hint: Explicit large q SYK results should help in generalizations
  [Choi, Haehl, MM, Sárosi, Streicher wip]

- How to derive the membrane theory from EFT reasoning?
  How to relate $\mathcal{E}(v)$ to other quantities?
  Hint: v_B determines the endpoint of $\mathcal{E}(v)$

Open questions

Open questions and some hints

- EFT for operator growth? Relation to Schwarzian, Reggeon field theory?
  Hint: Explicit large q SYK results should help in generalizations
  [Choi, Haehl, MM, Sárosi, Streicher wip]

- How to derive the membrane theory from EFT reasoning?
  How to relate $\mathcal{E}(v)$ to other quantities?
  Hint: v_B determines the endpoint of $\mathcal{E}(v)$

- Unifying EFT in the hydro limit?
  Hint: EFT for maximal chaos explains pole skipping [Blake, Lee, Liu]
  Membrane theory interplay with hydro, key role of v_B

Open questions

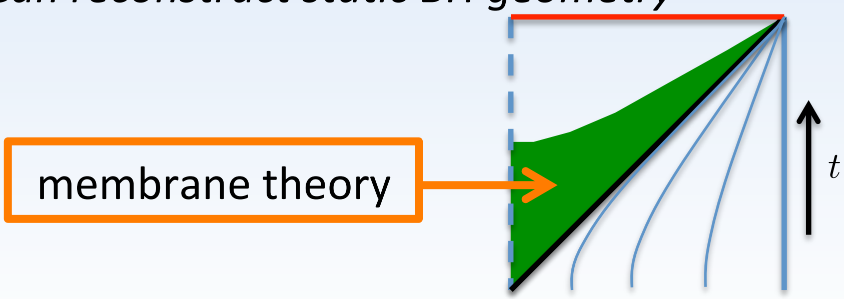
Open questions and some hints

- EFT for operator growth? Relation to Schwarzian, Reggeon field theory?
  Hint: Explicit large q SYK results should help in generalizations
  [Choi, Haehl, MM, Sárosi, Streicher wip]

- How to derive the membrane theory from EFT reasoning?
  How to relate $\mathcal{E}(v)$ to other quantities?
  Hint: v_B *determines the endpoint of* $\mathcal{E}(v)$

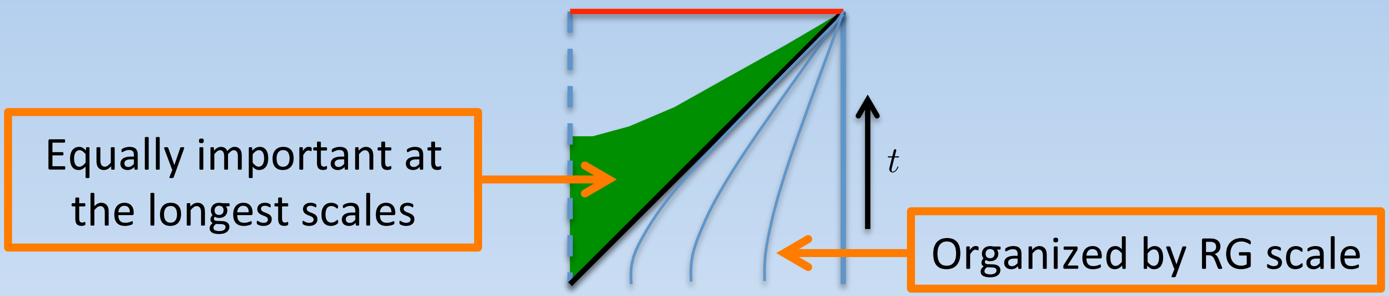
- Unifying EFT in the hydro limit?
  Hint: EFT for maximal chaos explains pole skipping [Blake, Lee, Liu]
  Membrane theory interplay with hydro, key role of v_B

- "Gravity is the hydrodynamics of entanglement." Can we get GR from the membrane?
  Hint: Can reconstruct static BH geometry



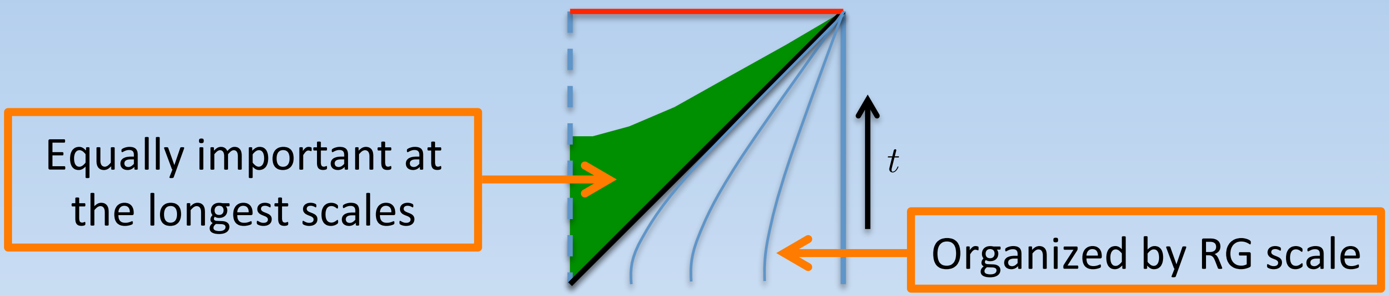
Open questions

- Implications for holographic RG?
  Hint: The metric inside the horizon does not seems to be organized by scale.



Open questions

- Implications for holographic RG?
  Hint: The metric inside the horizon does not seems to be organized by scale.



- Implications for tensor network approaches?
  Hint: Found a quantitative tensor network-like description, after partially solving the EOMs.