University of Zurich[UZH]

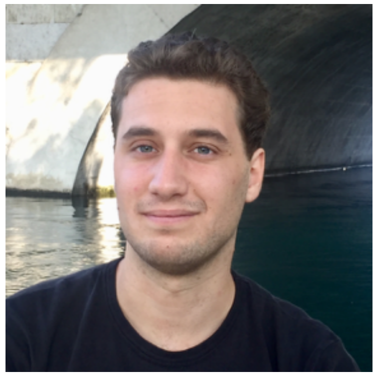
Emergent blackhole dynamics in critical Floquet systems

Titus Neupert

GGI, Sept 13, 2021

European Research Council

FNSNF Swiss National Science Foundation



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(ETH)

Clement Tauber
(Paris)

Phys. Rev. Research 2, 023085 (2020)
Phys. Rev. Research 2, 033461 (2020)


How do quantum systems heat up?

Outline

1. **Intro to Floquet theory, heating, and conformal field theory**

2. Solving a Floquet CFT problem

3. Propagation of excitations

4. Numerics for a lattice system

Bonus: Hyperbolic space in an electric circuit

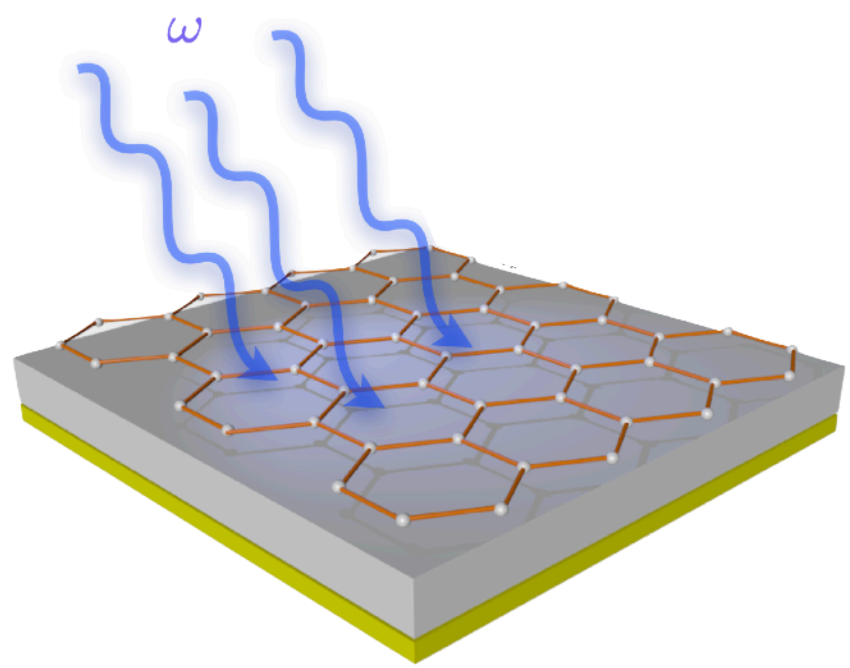
Floquet systems

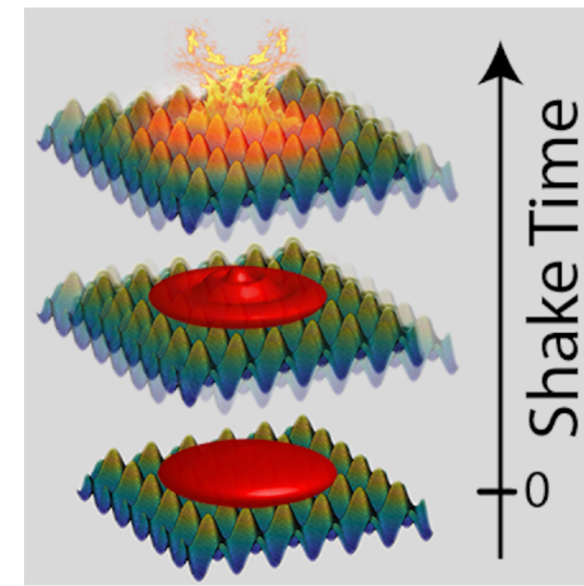
$$\left| \text{state at time t} \right\rangle = \exp\left[-i\int_{t_0}^{t} \mathrm{d}t' H(t')\right] \left| \text{initial state} \right\rangle$$

systems with time-periodic driving

no energy conservation

$$H(t) = H(t+nT)$$





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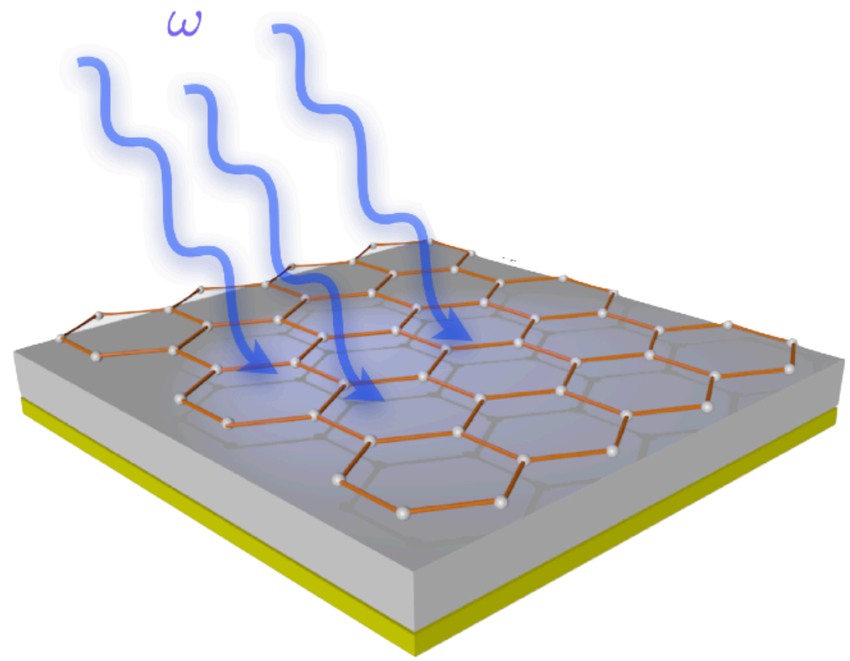
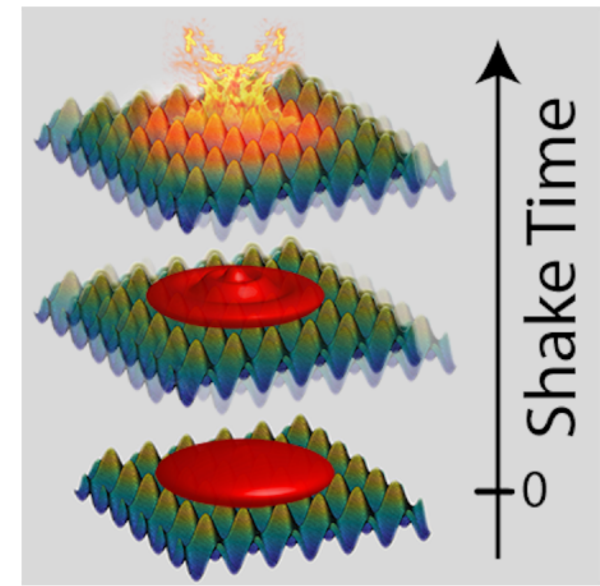




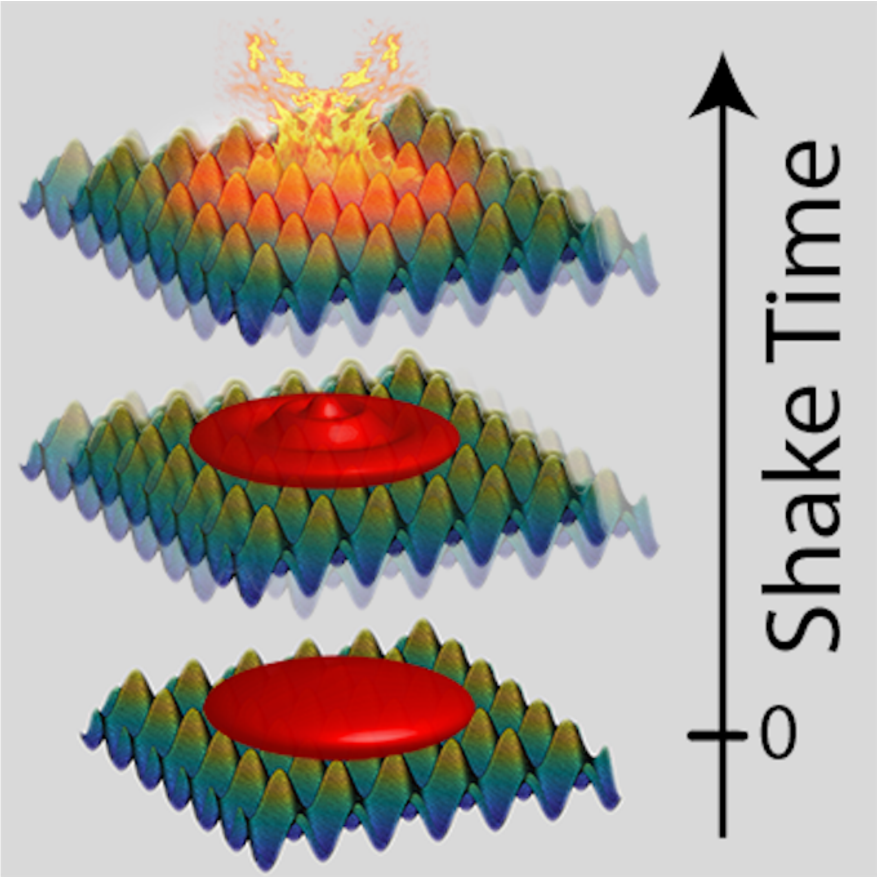
Floquet unitary: evolution by one period

$$\exp\left[-i\int_{t_0}^{t_0+T} \mathrm{d}t'\, H(t')\right] \equiv \exp\left[-iTH_{\mathrm{F}}\right]$$

Floquet Hamiltonian: exists, but not easy to compute and not short-ranged in generic interacting systems

Floquet systems: heating

Floquet systems: heating

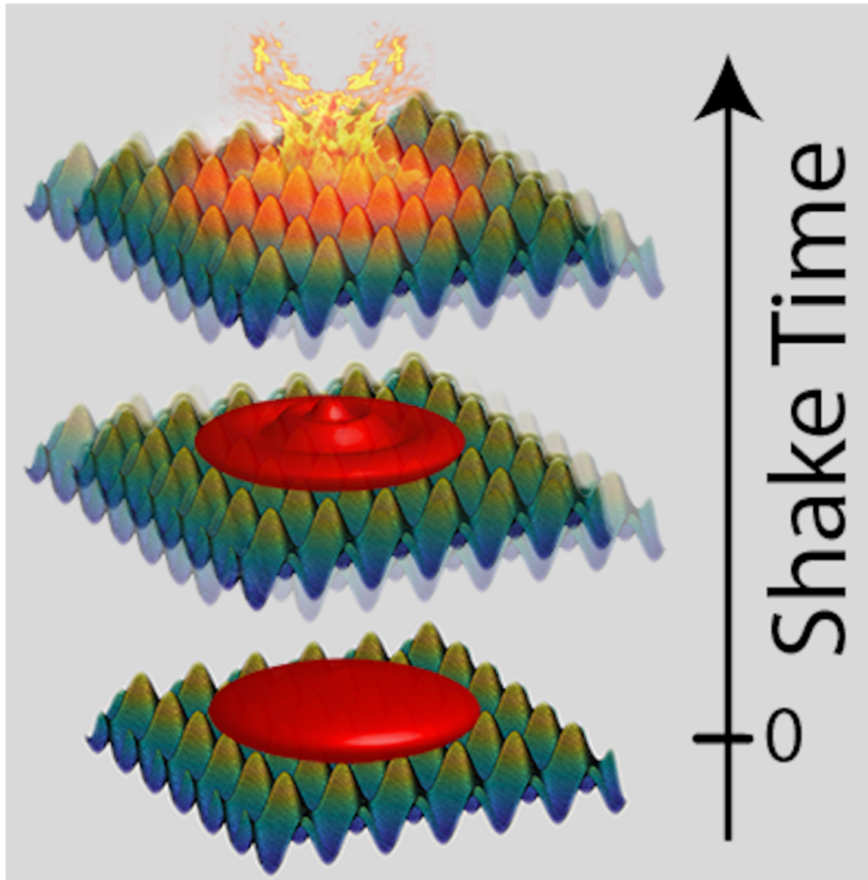


Isolated, driven and interacting systems thermalize (mostly)

D'Alessio & Rigol 2014

Lazarides, Das & Moessner 2014

Floquet systems: heating



Porto group, JQI

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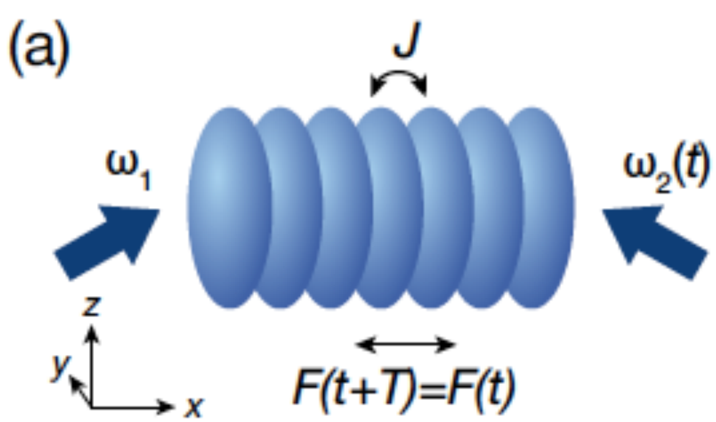
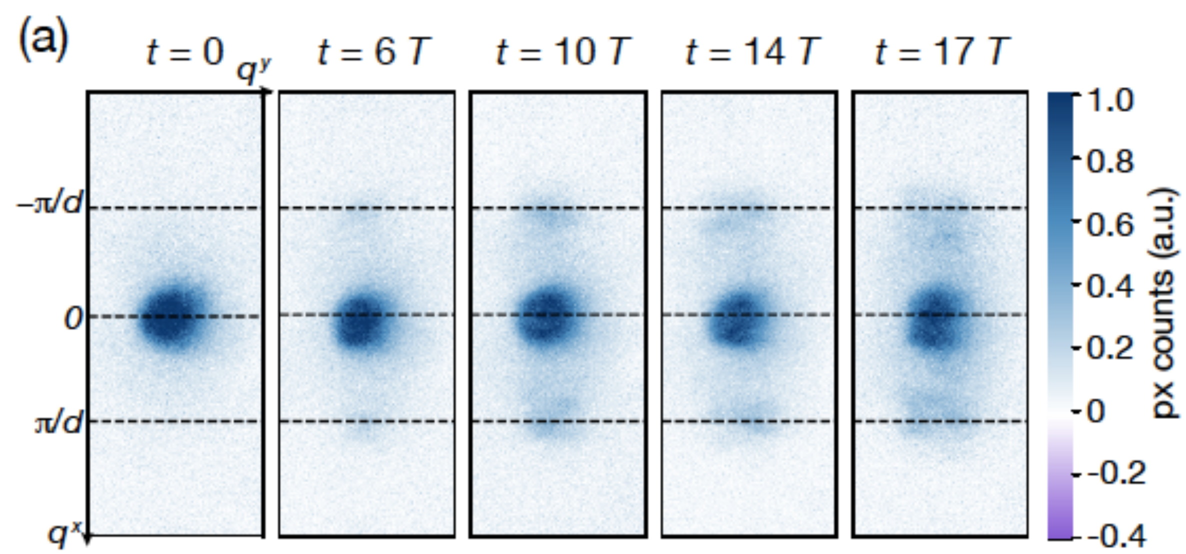
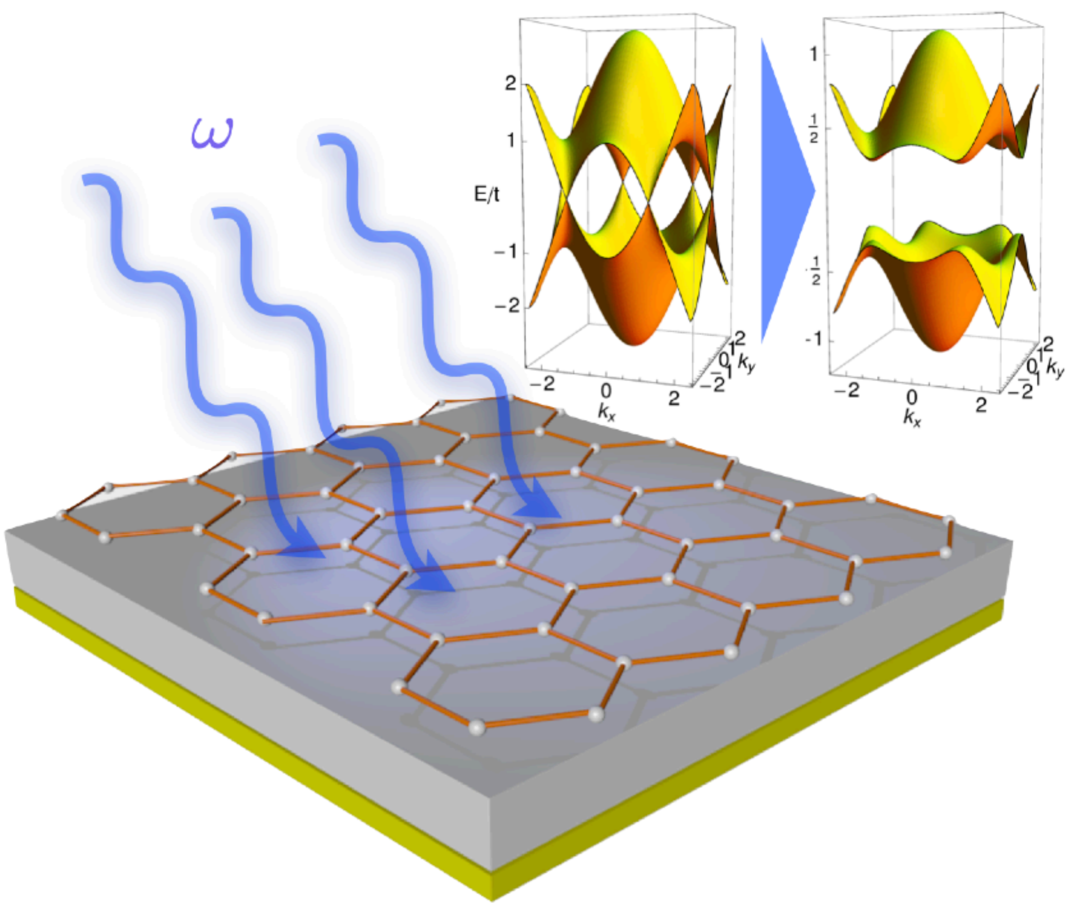




Wintersperger et al., Phys. Rev. X 10, 011030 (2020)

Floquet systems: irradiated graphene

Topological gap opening in
noninteracting graphene
by circularly polarized light



Kitagawa et al. 2011

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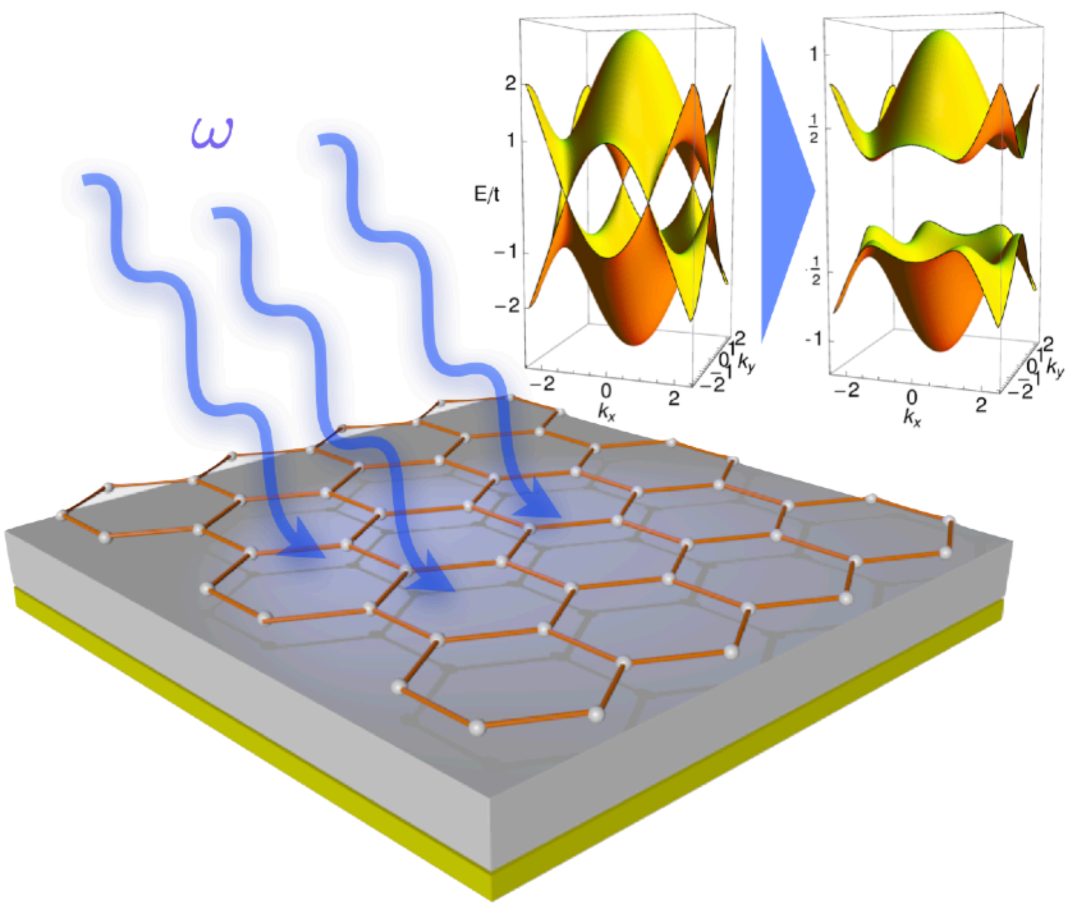
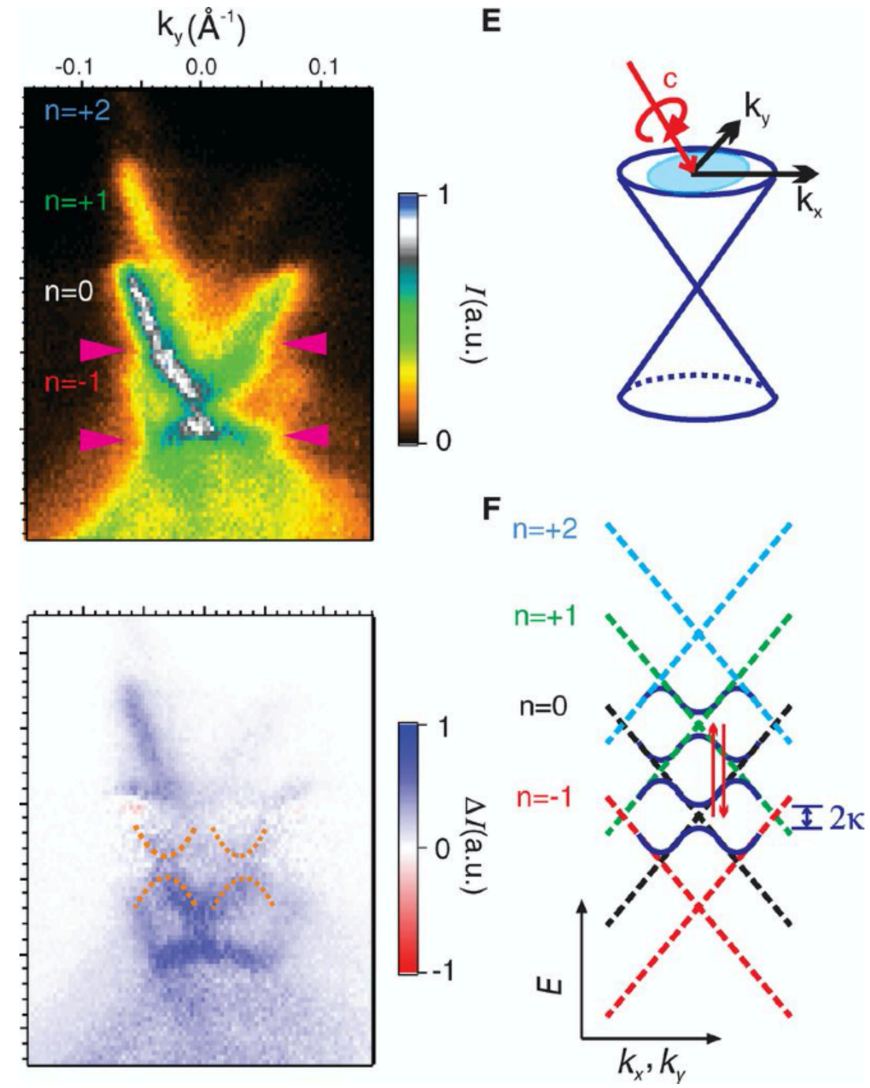
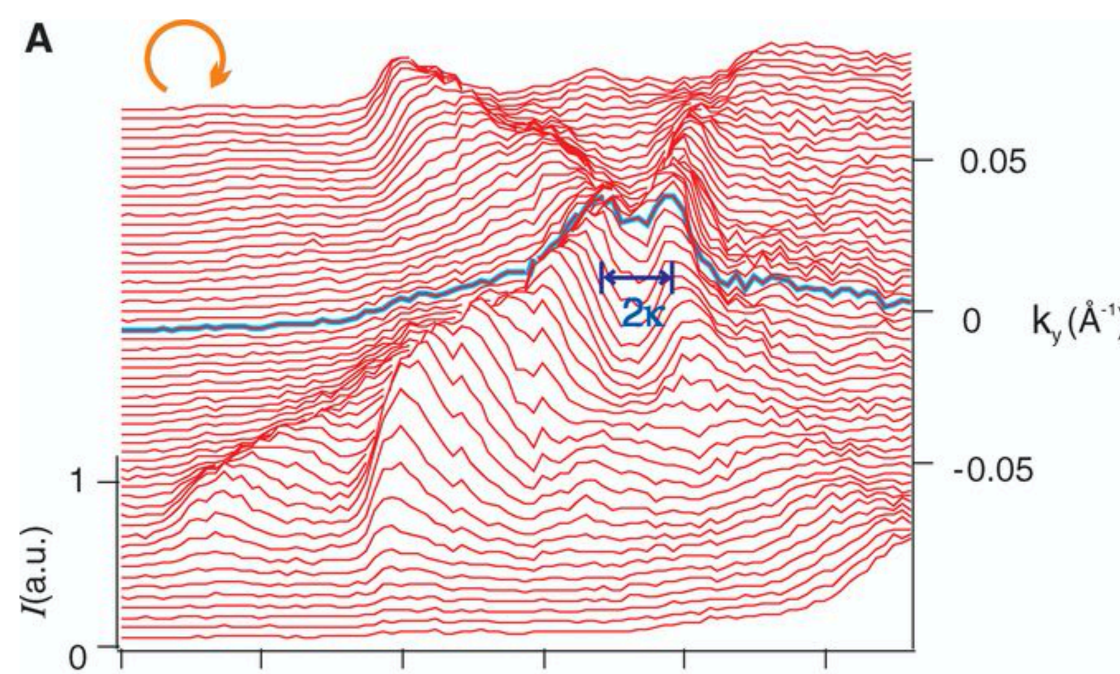


Kitagawa et al. 2011

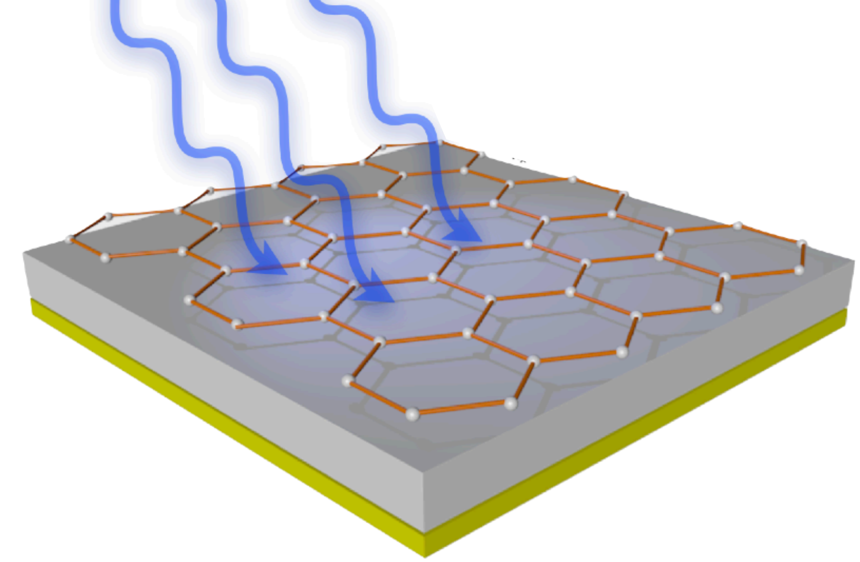
realization on
topological
insulator
surface





Wang et al. Science, 2013

Heating in isolated, driven systems

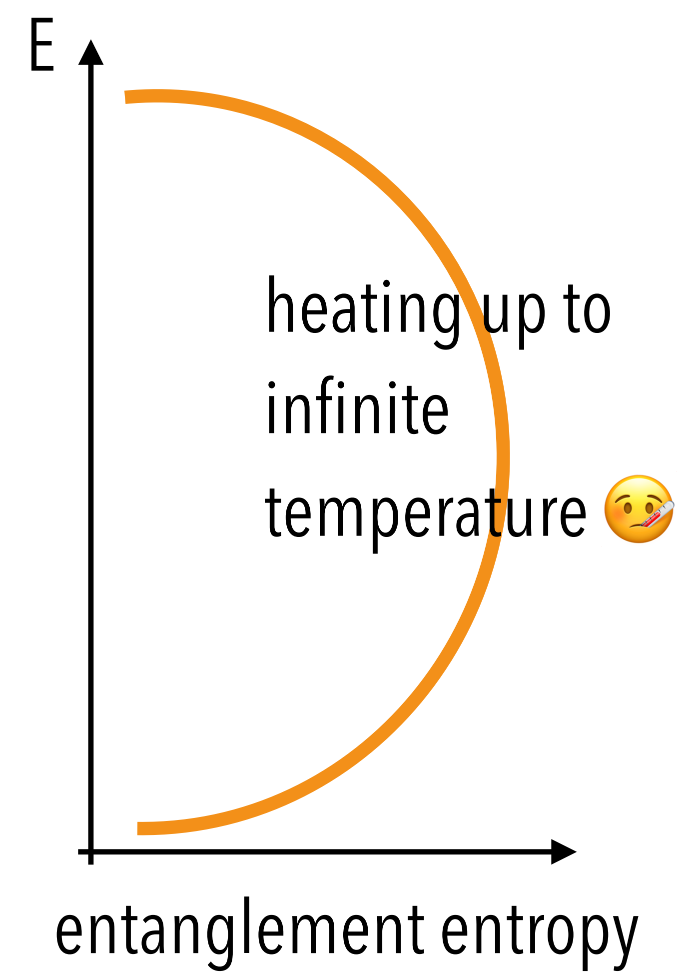


generic case:

thermalization

ETH

volume law entanglement



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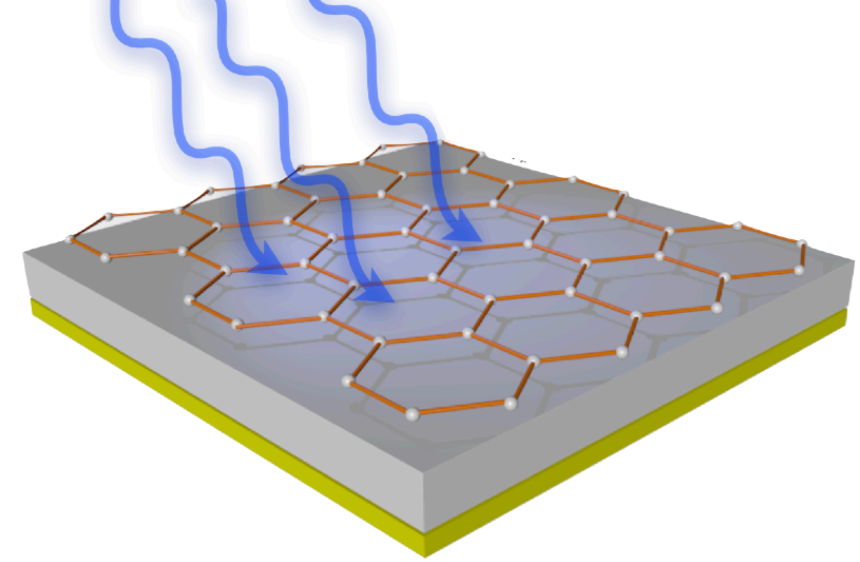

scar states:
isolated sub-volume law
states in the middle of
the spectrum

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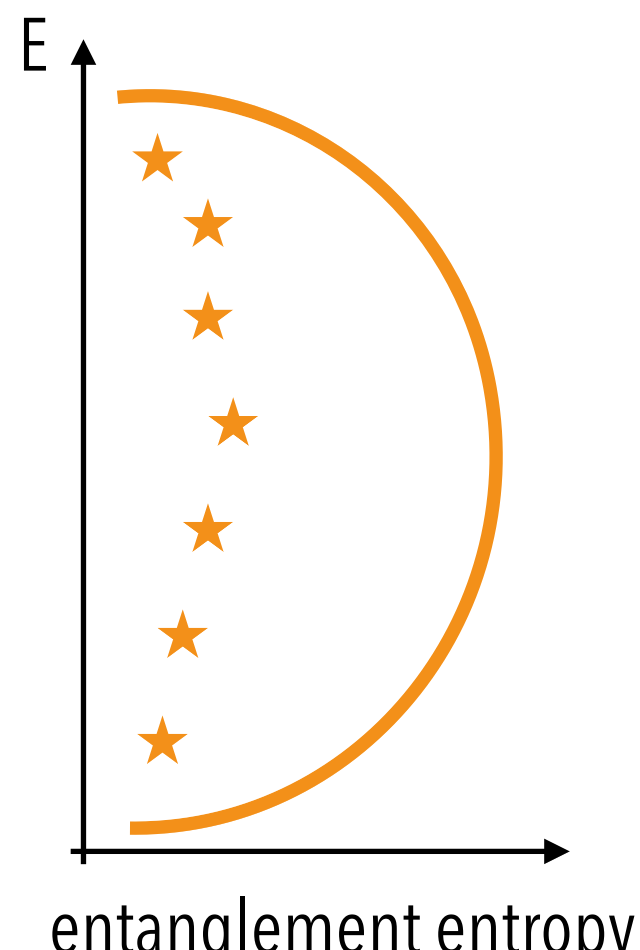

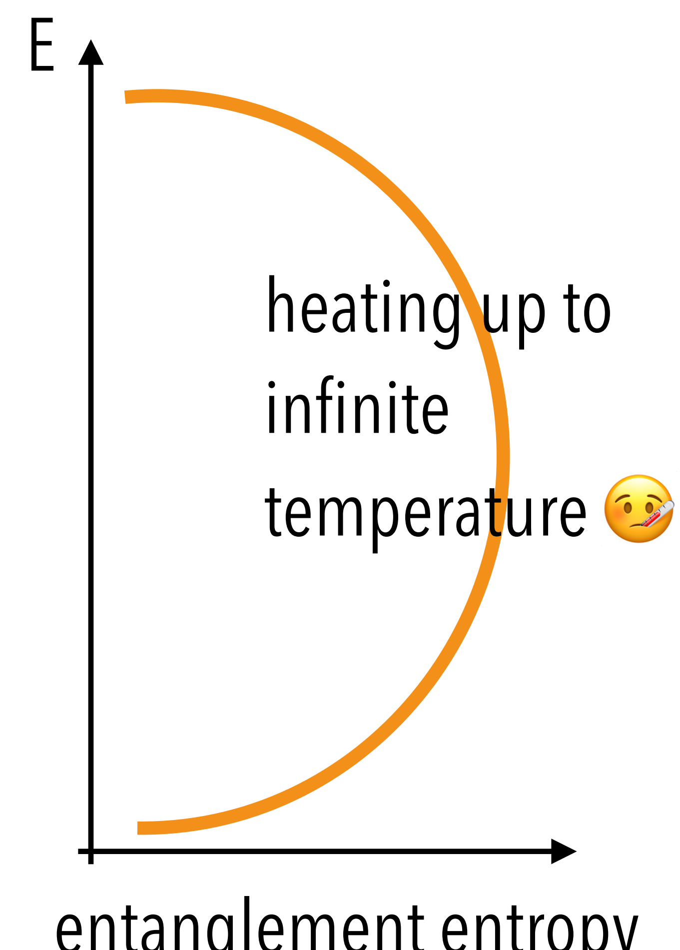

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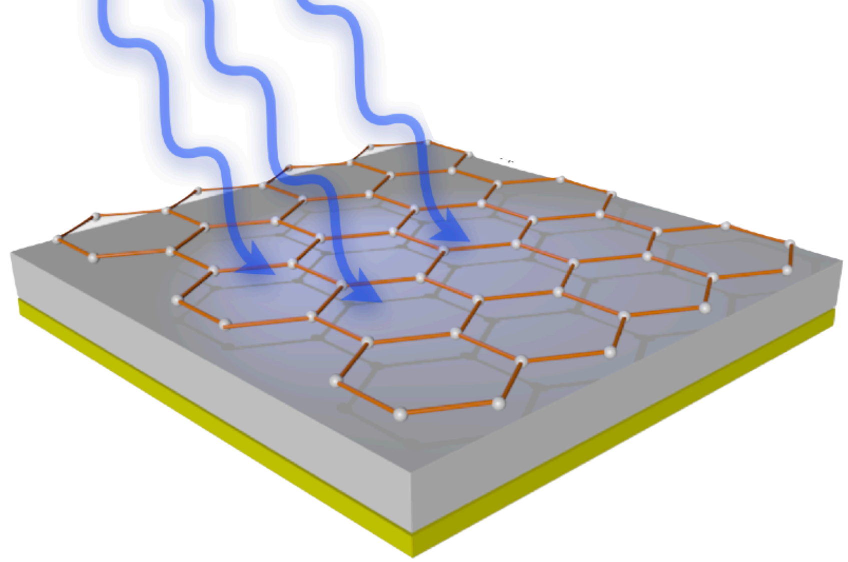

many-body localization:
all states area law entangled

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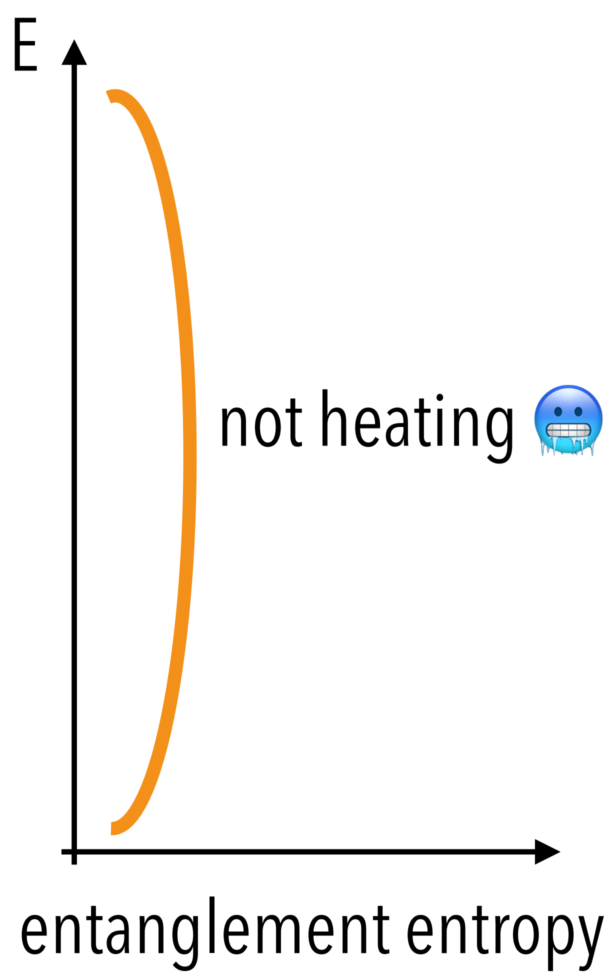
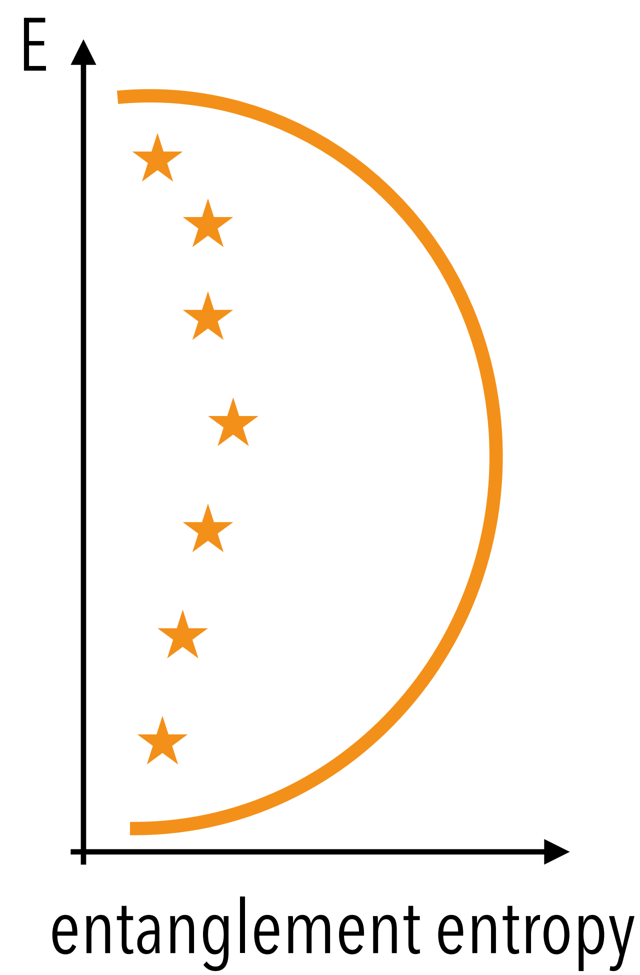
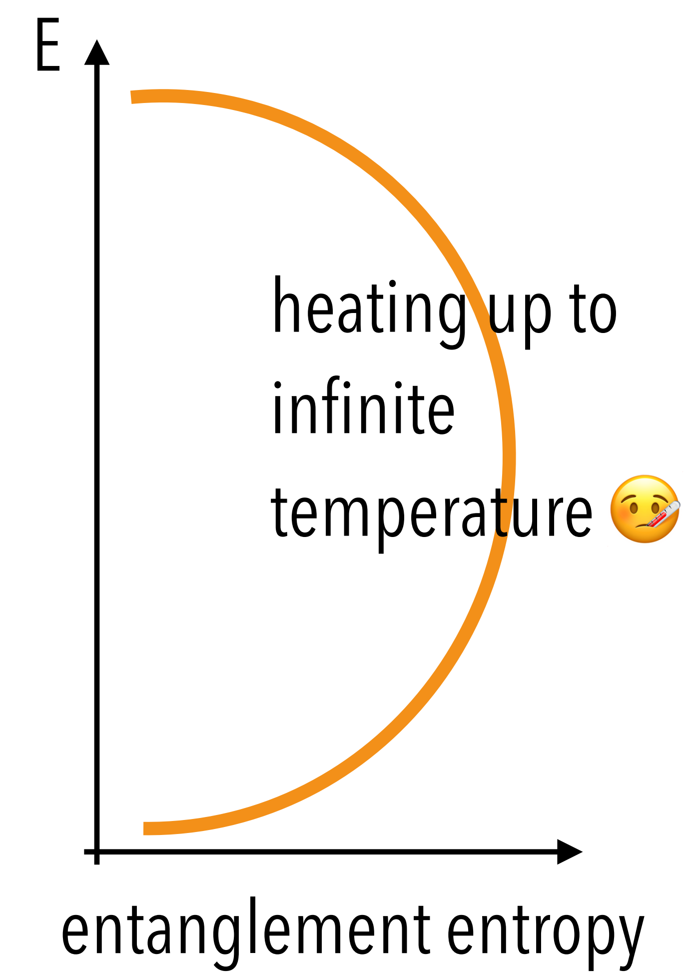
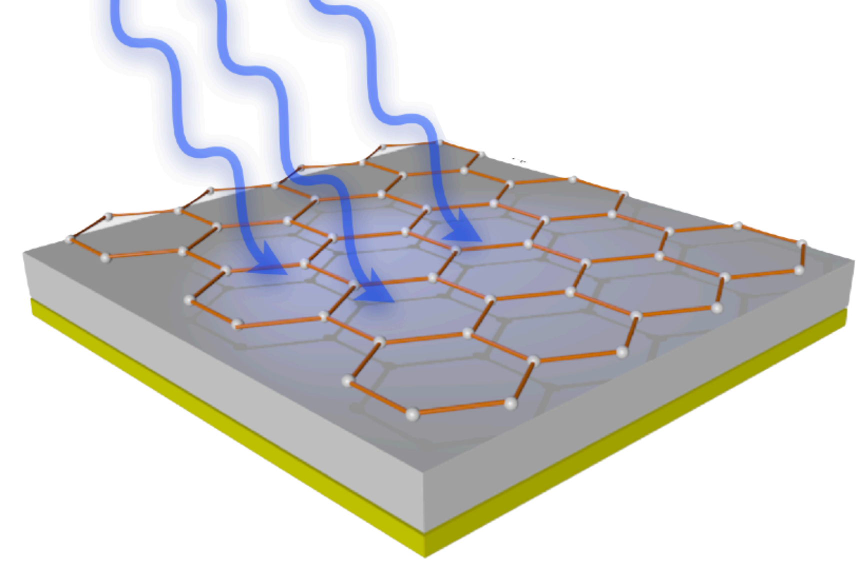






Heating in isolated, driven systems



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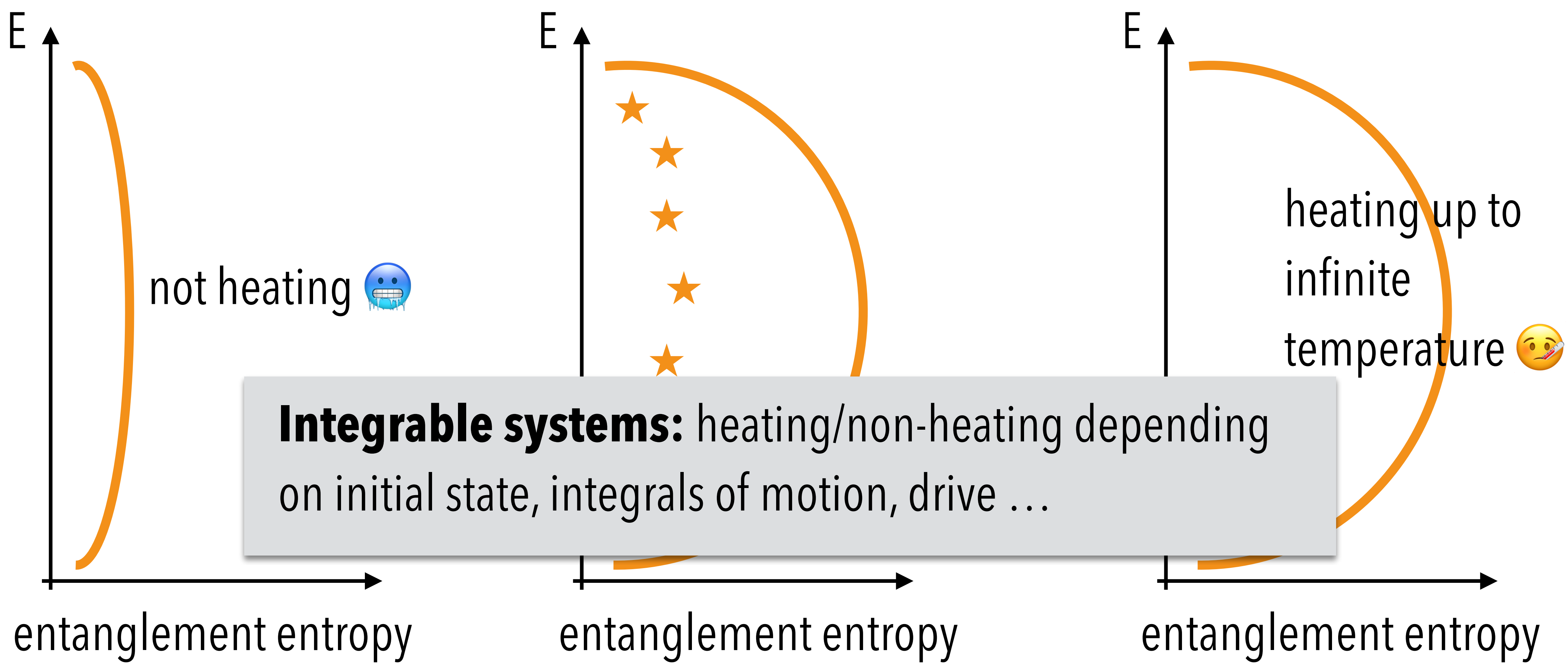

Integrable systems: heating/non-heating depending on initial state, integrals of motion, drive …

This talk: Case study of driven integrable system

🥶 🤒 heating and non-heating phases

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👯‍♀️ interacting particles

This talk: Case study of driven integrable system

- heating and non-heating phases
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- analytically exact calculation of floquet Hamiltonian and time evolution

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- 🌗 spatially structured heating phase

This talk: Case study of driven integrable system

🥶 🤒 heating and non-heating phases

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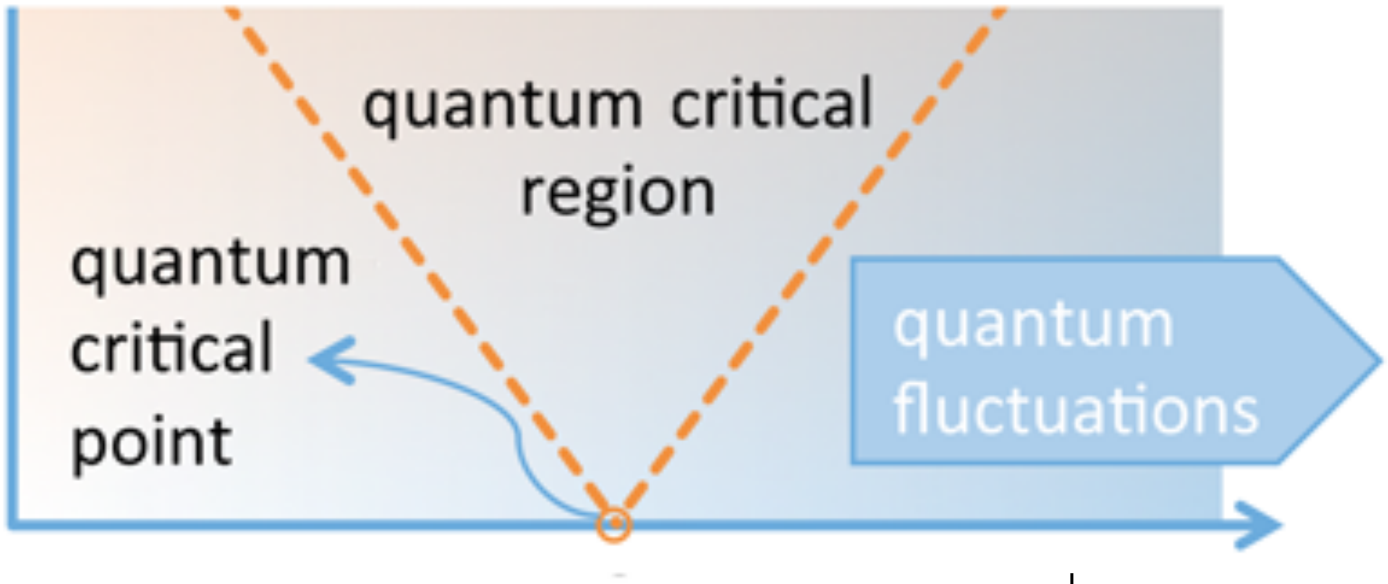
⏱️ analytically exact calculation of floquet Hamiltonian and time evolution

🌓 spatially structured heating phase

🏄 interpretation in terms of quasiparticle propagation

How does a driven system heat up?

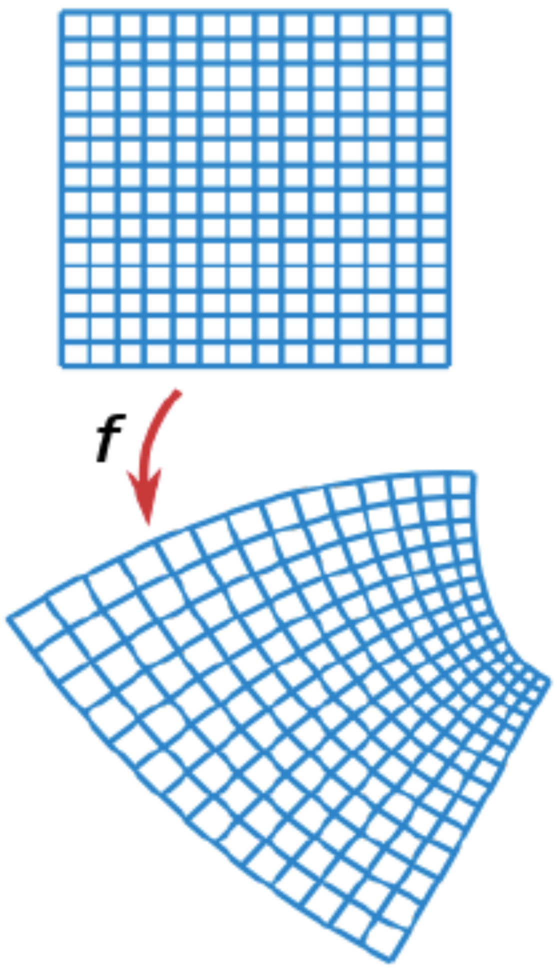


phys.org

Quantum critical systems in 1D

- scale invariant low energy theory
- conformal field theory

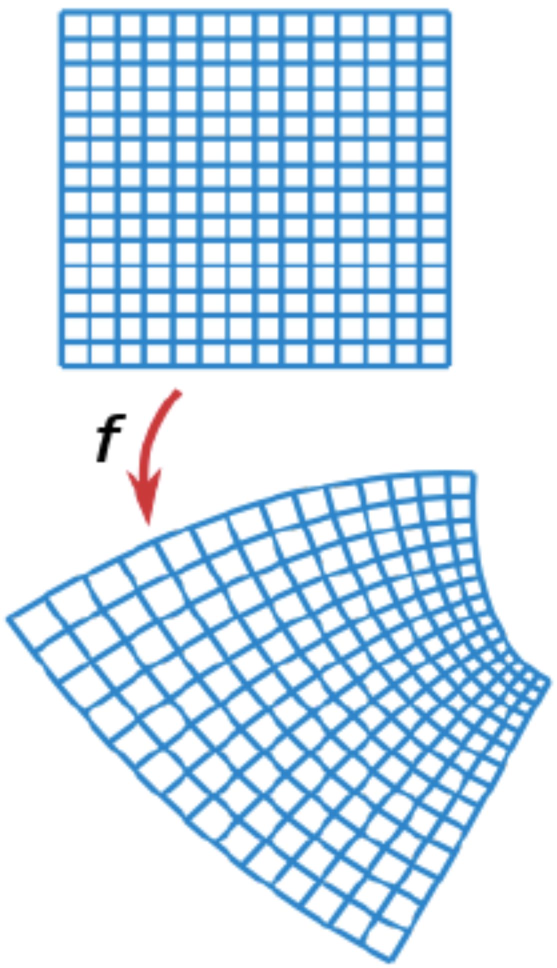
Conformal field theory



Invariance under conformal transformation (angle preserving maps)

scale invariance $\quad x \to \lambda x$

Conformal field theory



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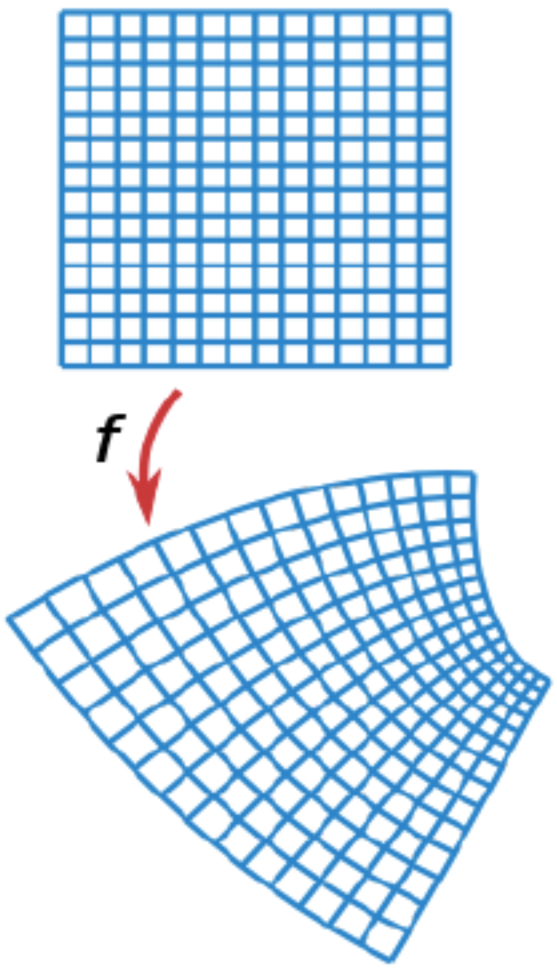
Infinite Virasoro algebra in 1+1 D

$$[L_m, L_n] = (m-n)L_{m+n} + \frac{c}{12}(m^3 - m)\delta_{m+n,0}$$

Central charge $c = \frac{1}{2}$ free fermions $c = 1$ free bosons

Conformal field theory



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Central charge $c = \frac{1}{2}$ $c = 1$

free fermions free bosons

Closed sub-algebra

Generators of global conformal group

$$[L_0, L_{-1}] = L_{-1}$$
$$[L_0, L_1] = -L_1$$
$$[L_1, L_{-1}] = 2L_0$$
$$L \rightarrow \overline{L}$$

$$SL(2, \mathbb{C})$$

rotations,
dilations,
translations,
special conformal trans

CFT Hamiltonian $$\mathcal{H}_0 = \frac{2\pi}{L}(L_0 + \bar{L}_0)$$

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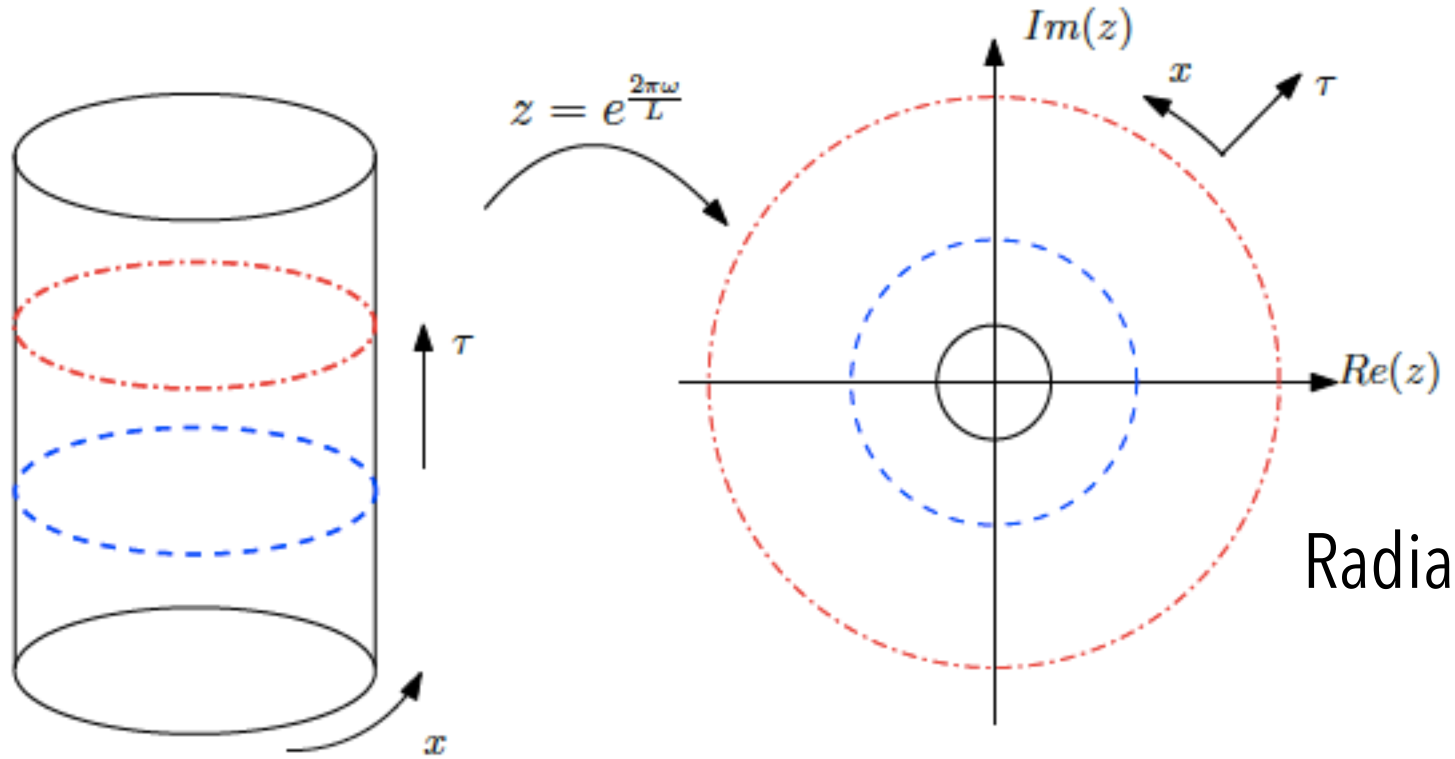

Radial quantization

time translation ⟷ dilation in z plane

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Bonus: Hyperbolic space in an electric circuit

Floquet drive

CFT Hamiltonian

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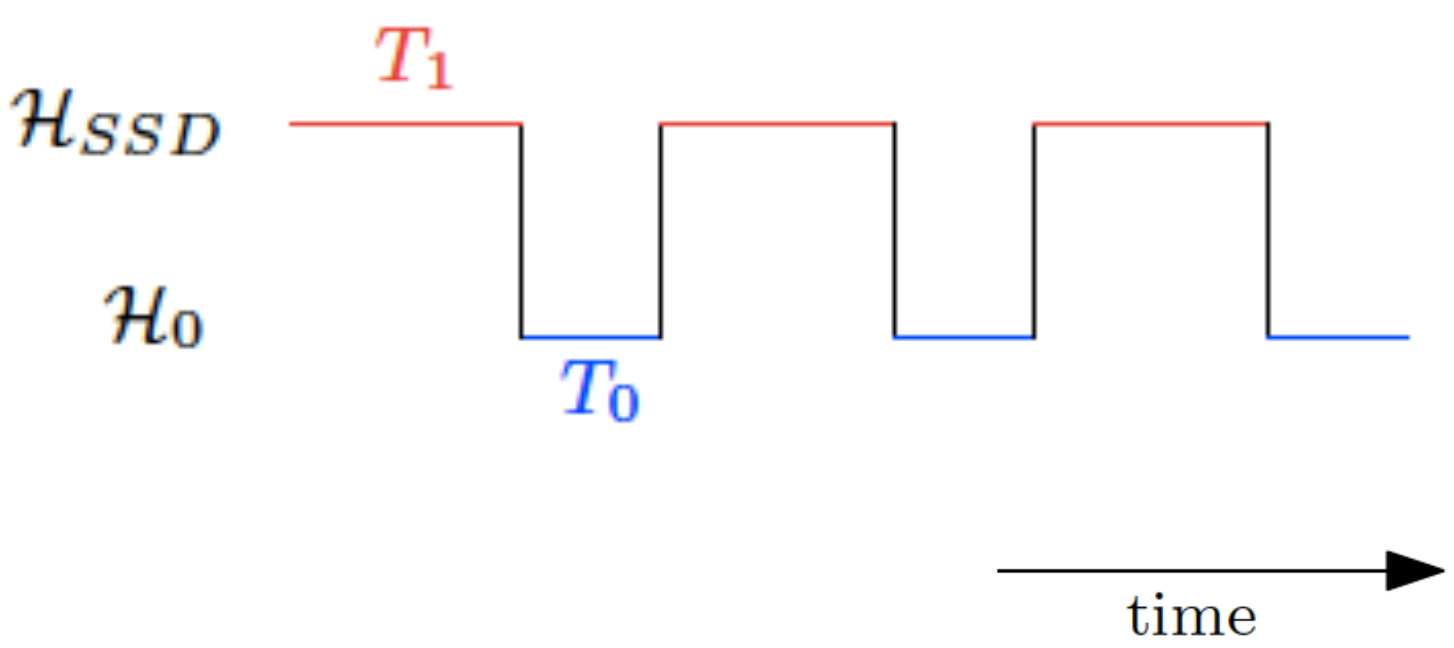
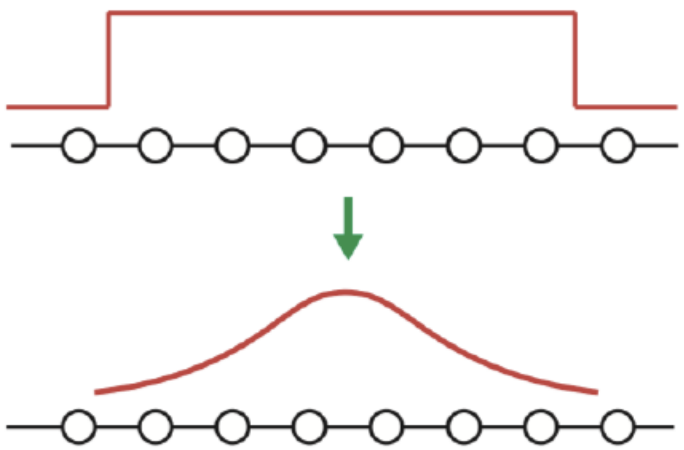


Does the system heat up ?

Sine-Square Deformations



$$\mathcal{H}_0 = \sum_{j=1}^{L} h_{j,j+1} + \sum_{j=1}^{L} h_j$$

$$\mathcal{H}_{\text{SSD}} = \sum_{j=1}^{L} f_{j+\frac{1}{2}} h_{j,j+1} + \sum_{j=1}^{L} f_j h_j$$

$$f_x = \sin^2\left[\tfrac{\pi}{L}\left(x - \tfrac{1}{2}\right)\right]$$

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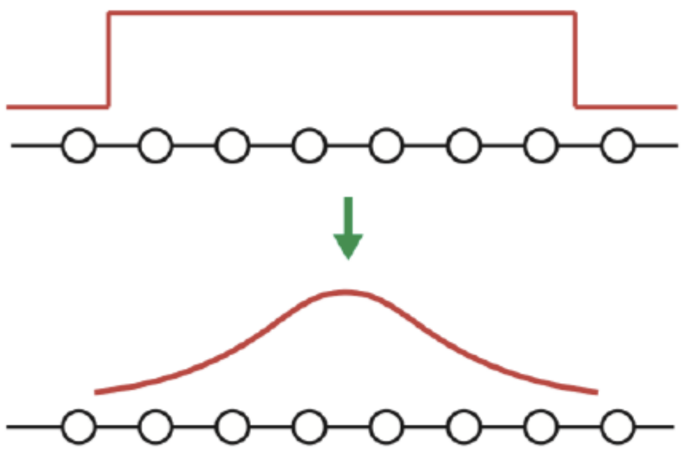

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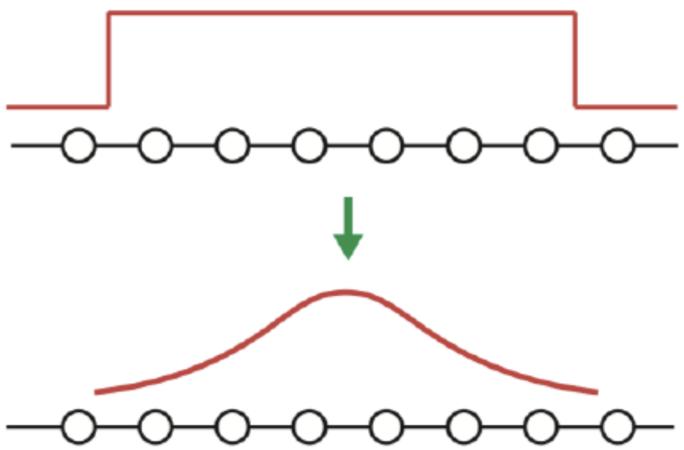
Trick to eliminate boundary effects

Asano & Hotta 2018

Sine-Square Deformations



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Ground state:

Trick to eliminate boundary effects

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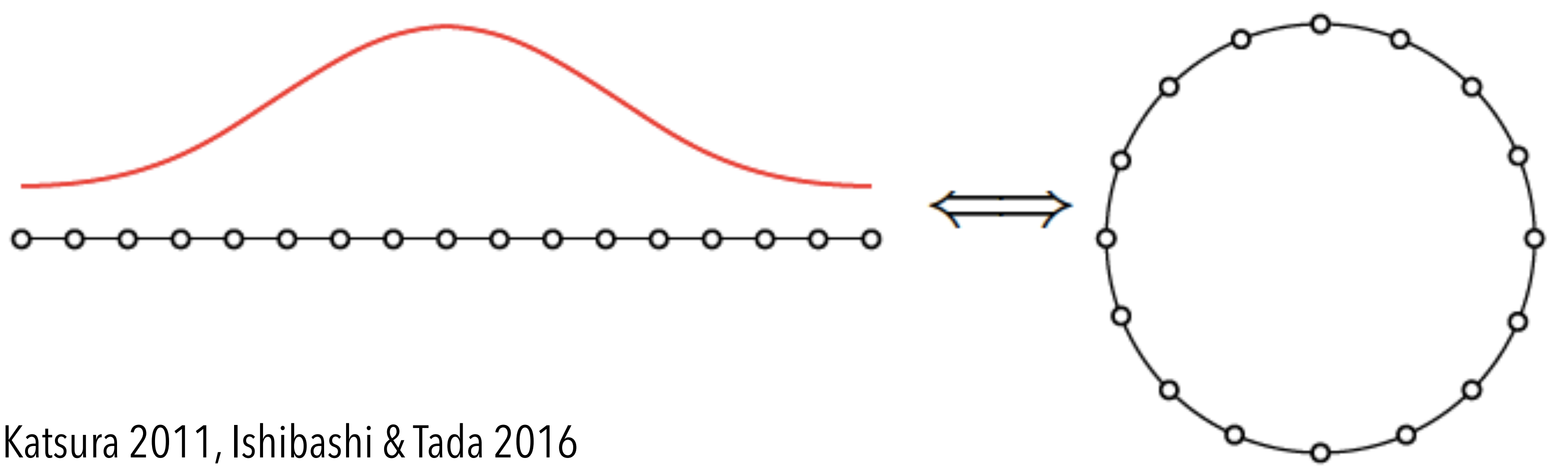
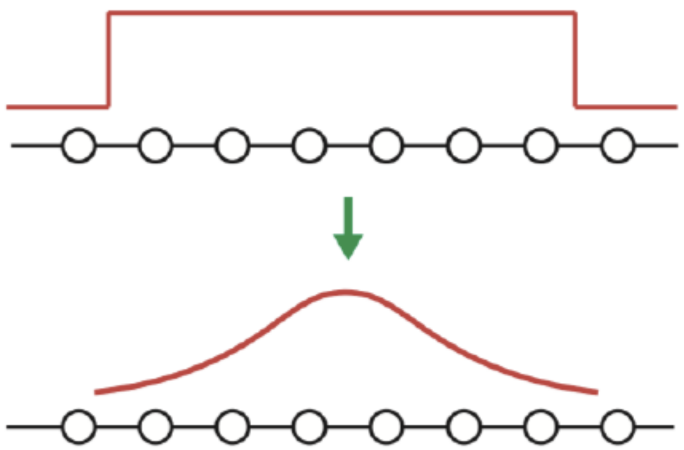


Katsura 2011, Ishibashi & Tada 2016

Sine-Square Deformations



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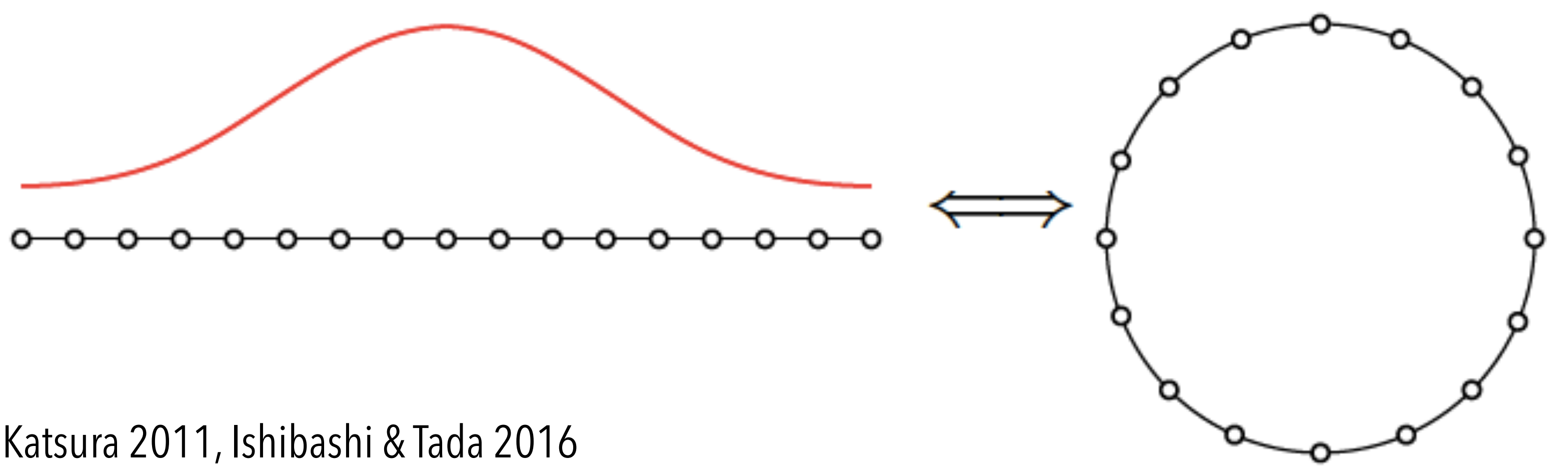

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Hamiltonian: $\mathcal{H}_{\rm SSD} = L_0 - \frac{1}{2}(L_1 + L_{-1}) + \overline{L}_0 - \frac{1}{2}(\overline{L}_1 + \overline{L}_{-1})$

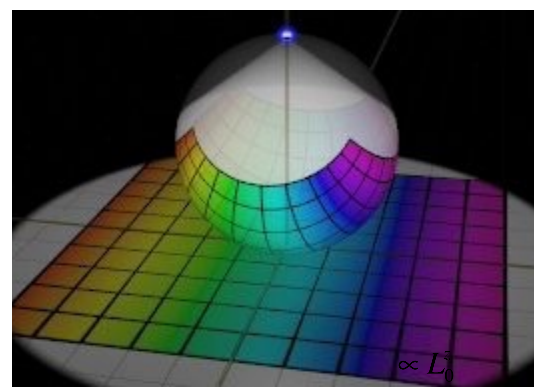
Sine-square deformation and Möbius transformation

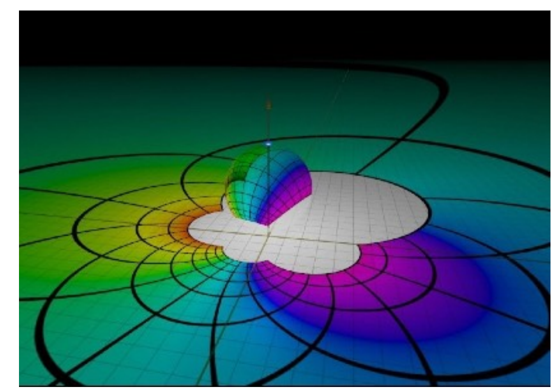
$$\mathcal{H}_0 = \frac{2\pi}{L}(L_0 + \bar{L}_0)$$

$$\mathcal{H}_{\mathrm{SSD}} = L_0 - \tfrac{1}{2}(L_1 + L_{-1}) + \overline{L}_0 - \tfrac{1}{2}(\overline{L}_1 + \overline{L}_{-1})$$

Möbius transformation

$$\tilde{z}(z) = \frac{az+b}{cz+d}$$





Ishibashi, Okunishi, Tada 2016

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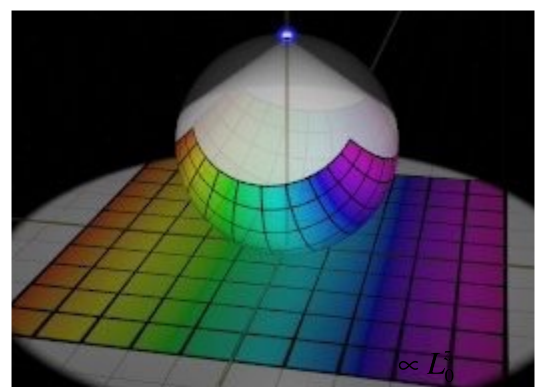

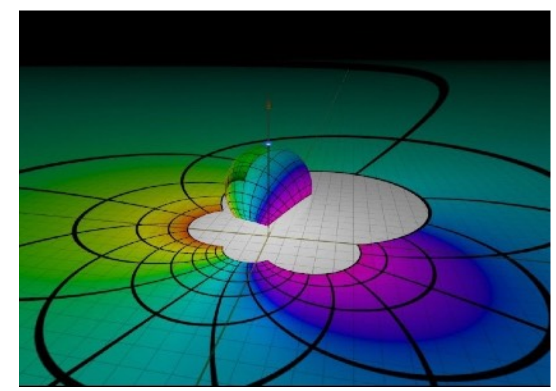

in particular

Ishibashi, Okunishi, Tada 2016

$$\hat{z} = f(z) = \frac{-\cosh(\theta)z + \sinh(\theta)}{\sinh(\theta)z - \cosh(\theta)}$$

$$\mathcal{H}_{\mathrm{M\ddot{o}b}(\theta)} = L_0 - \frac{\tanh(2\theta)}{2}(L_1 + L_{-1}) + \overline{L}_0 - \frac{\tanh(2\theta)}{2}(\overline{L}_1 + \overline{L}_{-1})$$ in z coordinates

$$\mathcal{H}_{\mathrm{M\ddot{o}b}(\theta)} \propto \tfrac{2\pi}{L\cosh(2\theta)}(L_0 + \overline{L}_0)$$ in $\hat{z}$ coordinates

Sine-square deformation and Möbius transformation

$$\mathcal{H}_0 = \frac{2\pi}{L}(L_0 + \bar{L}_0)$$

$$\mathcal{H}_{\mathrm{SSD}} = L_0 - \tfrac{1}{2}(L_1 + L_{-1}) + \overline{L}_0 - \tfrac{1}{2}(\overline{L}_1 + \overline{L}_{-1})$$

in z coordinates

interpolation

$$\mathcal{H}_0 = \mathcal{H}_{\mathrm{M\ddot{o}b}(0)} \qquad \mathcal{H}_{\mathrm{SSD}} = \mathcal{H}_{\mathrm{M\ddot{o}b}(\theta\to\infty)}$$

$$\mathcal{H}_{\mathrm{M\ddot{o}b}(\theta)} \propto \frac{2\pi}{L\cosh(2\theta)}(L_0 + \overline{L}_0)$$

Sine-square deformation and Möbius transformation

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in z coordinates

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$$\mathcal{H}_0 = \mathcal{H}_{\mathrm{Möb}(0)} \qquad \mathcal{H}_{\mathrm{SSD}} = \mathcal{H}_{\mathrm{Möb}(\theta\to\infty)}$$

Time evolution by $\mathcal{H}_{\mathrm{Möb}(\theta)}$

in $\hat{z}$ coordinates

simple dilation by factor

$$\lambda = \exp\left\{\frac{2\pi\tau}{L\cosh 2\theta}\right\}$$

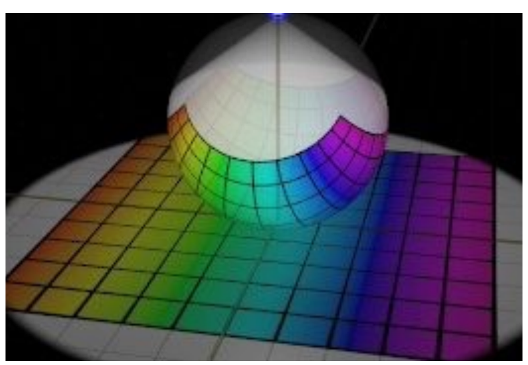
in z coordinates

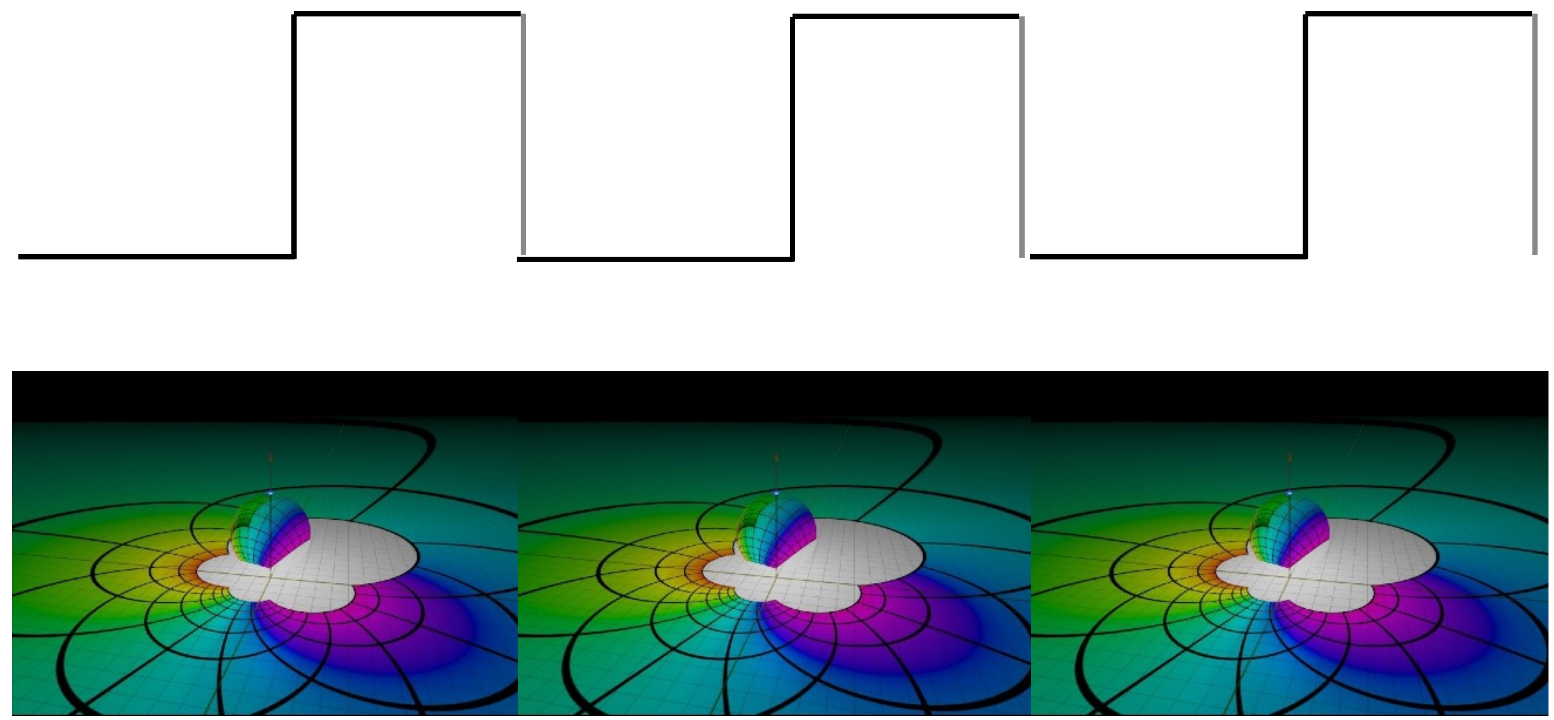
change of coordinates

$$z_\theta^{\mathrm{new}}(z) = f^{-1}(\lambda f(z))$$

$$\mathcal{H}_{\mathrm{Möb}(\theta)} \propto \frac{2\pi}{L\cosh(2\theta)}(L_0 + \overline{L}_0)$$

Dynamics – composition of Möbius transformations





Floquet Hamiltonian: exact

$$\mathcal{H}_{\mathrm{eff}} = \alpha \left[L_0 - \frac{\beta}{2}(L_1 + L_{-1}) + \bar{L}_0 - \frac{\beta}{2}(\bar{L}_1 + \bar{L}_{-1}) \right]$$

$$\beta^{-1} = \cos(\tfrac{\pi T_0}{L}) + \tfrac{L}{\pi T_1} \sin(\tfrac{\pi T_0}{L})$$

Wen & Wu 2018

Floquet Hamiltonian: exact

$$\mathcal{H}_{\text{eff}} = \alpha \left[L_0 - \frac{\beta}{2}(L_1 + L_{-1}) + \bar{L}_0 - \frac{\beta}{2}(\bar{L}_1 + \bar{L}_{-1}) \right]$$

$$\beta^{-1} = \cos\left(\frac{\pi T_0}{L}\right) + \frac{L}{\pi T_1}\sin\left(\frac{\pi T_0}{L}\right)$$

Heating phase $|\beta| > 1$

Nonheating phase $|\beta| < 1$

unbounded from below

Wen & Wu 2018

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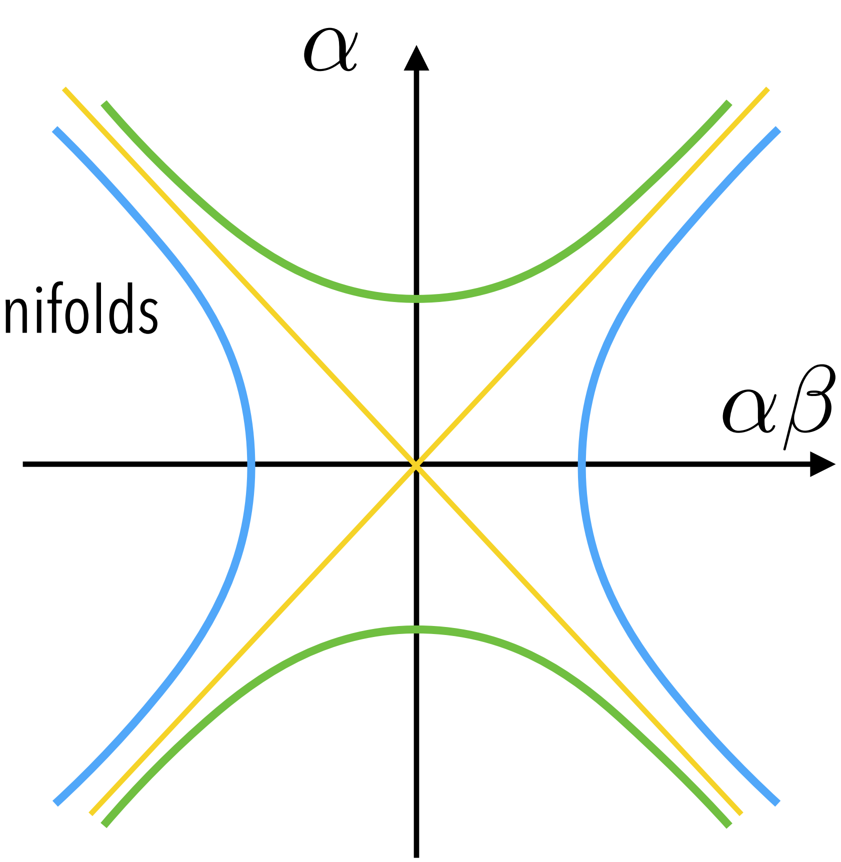
$SL(2,\mathbb{R})$-related manifolds

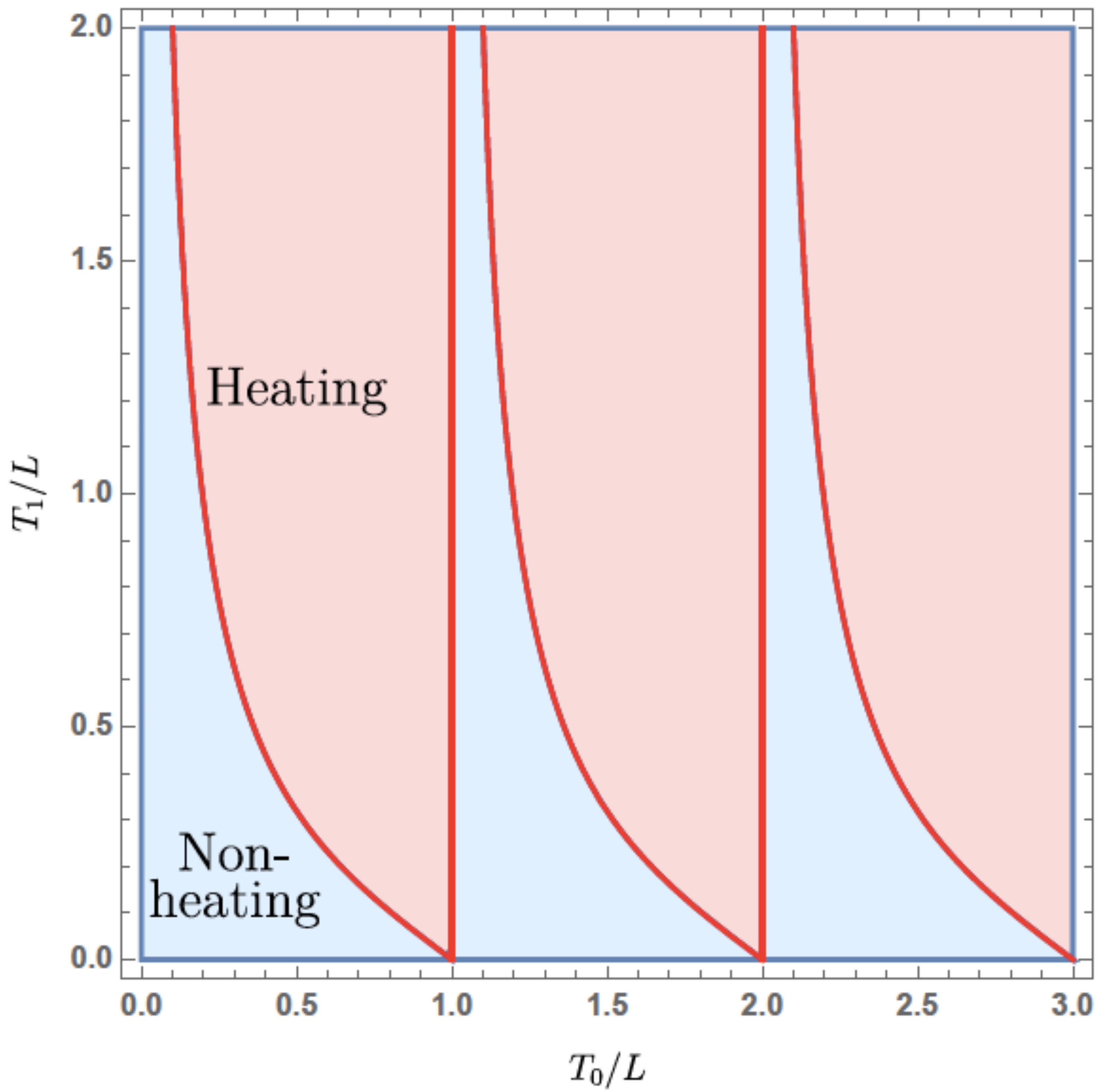


Casimir $SL(2,\mathbb{R})$

$$c^{(2)} = \alpha^2(1-\beta^2)$$

Wen & Wu 2018

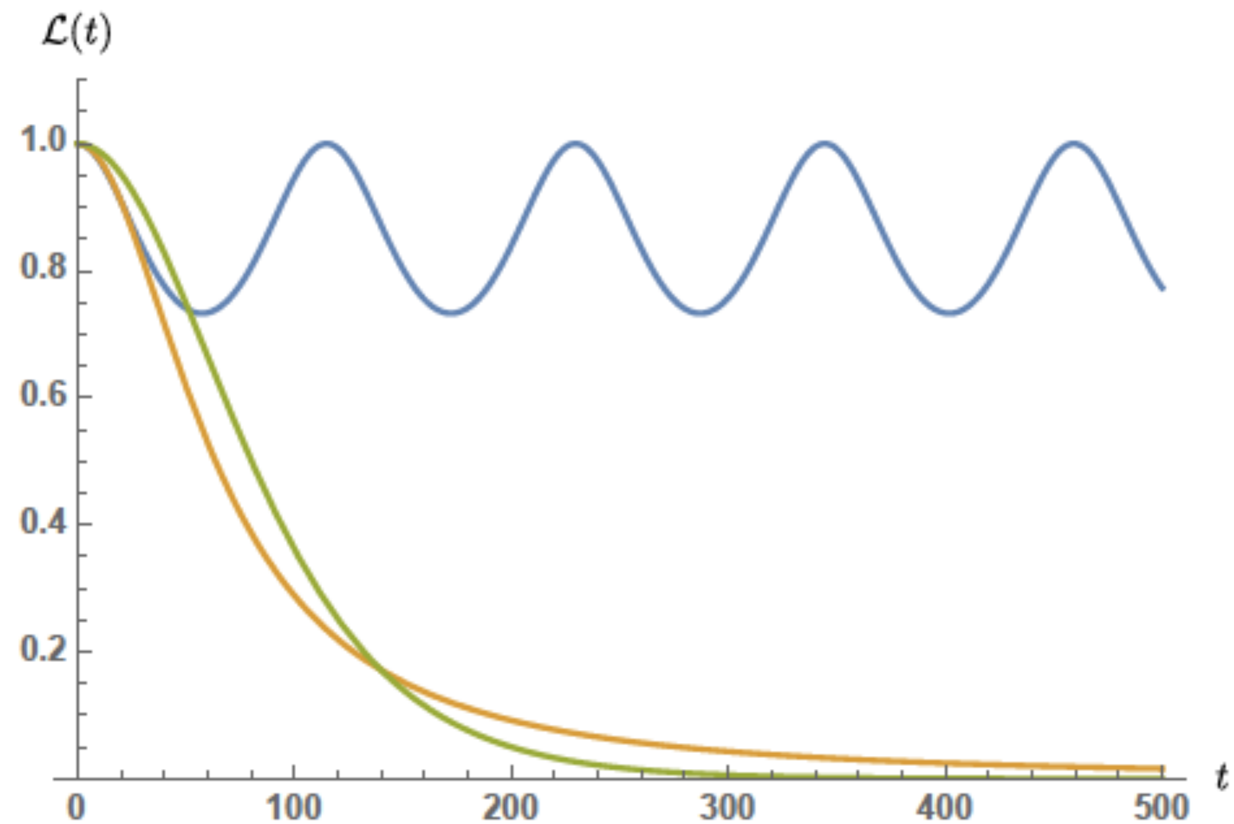
Dynamics – composition of Möbius transformations



Wen & Wu 2018

Entanglement entropy and Loschmidt echo

$$\mathcal{L}(t) = |\langle G| \underbrace{e^{-iH_0T_0}e^{-iH_{\mathrm{SSD}}T_1} \ldots e^{-iH_0T_0}e^{-iH_{\mathrm{SSD}}T_1}}_{\text{N times}} |G\rangle|^2$$



	Quench	Non-heating	Heating	Phase transition
$S_A(t)$	$\log(t)$	oscillating	t	$\log(t)$
$\mathcal{L}(t)$	$1/(1+t^2)$	oscillating	e^{-t}	$1/(1+t^2)$

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3. **Propagation of excitations**

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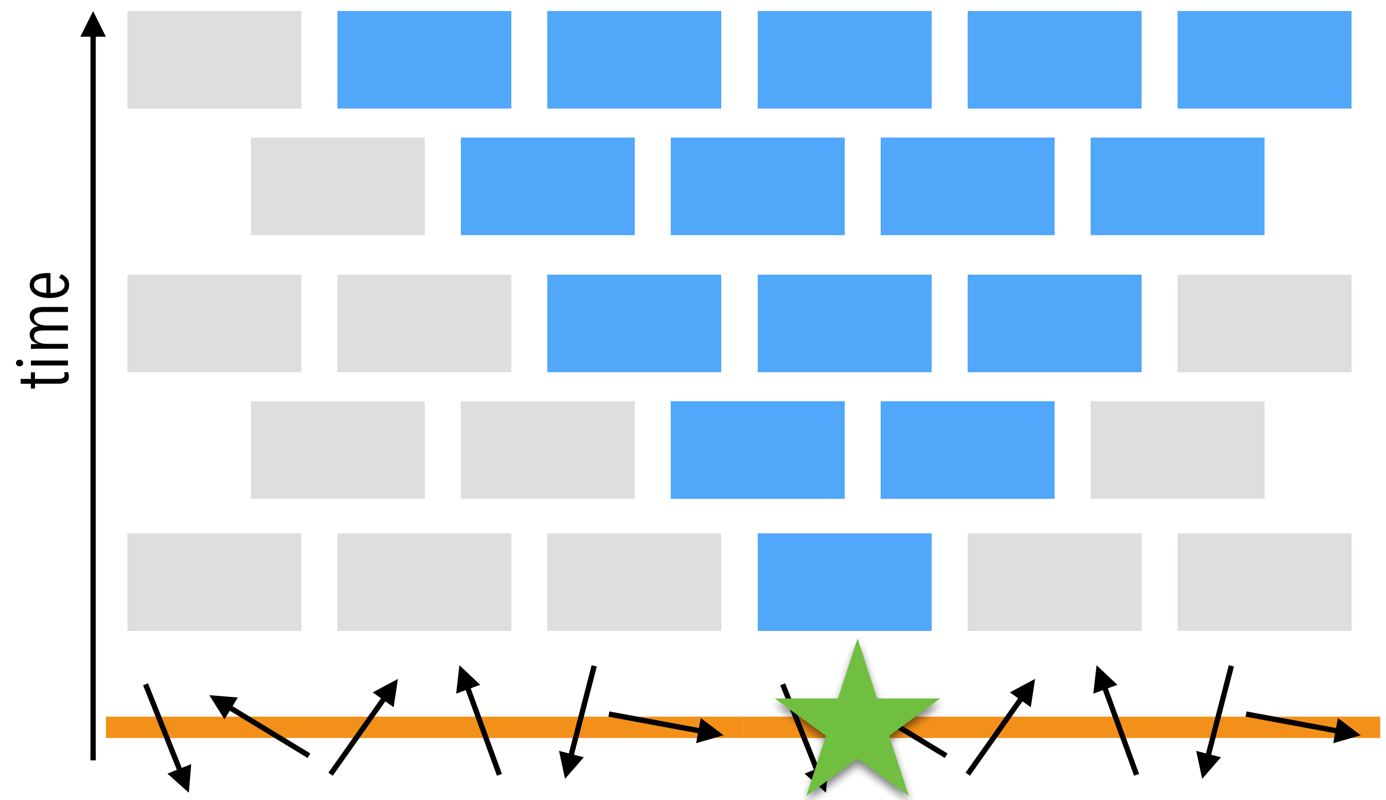
Bonus: Hyperbolic space in an electric circuit

Quantum circuit perspective:
information spreading in interacting quantum states

translationally
invariant
system



C. v. Keyserlingk et al PRX (2018)

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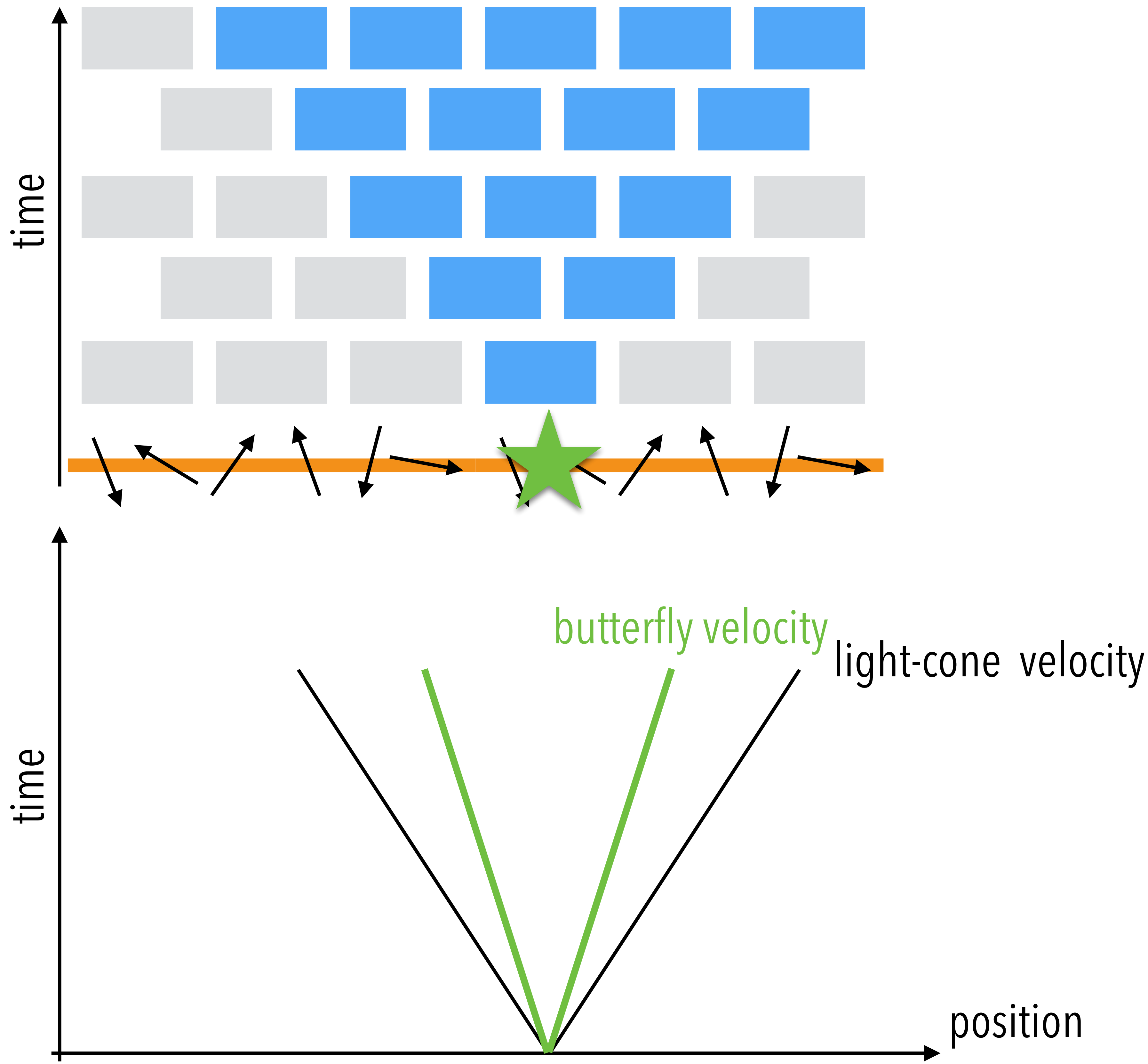

C. v. Keyserlingk et al PRX (2018)

Correlations $\langle G|\phi(x,t)\phi(x_0,0)|G\rangle$

Dubail et al

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No driving

Dubail et al

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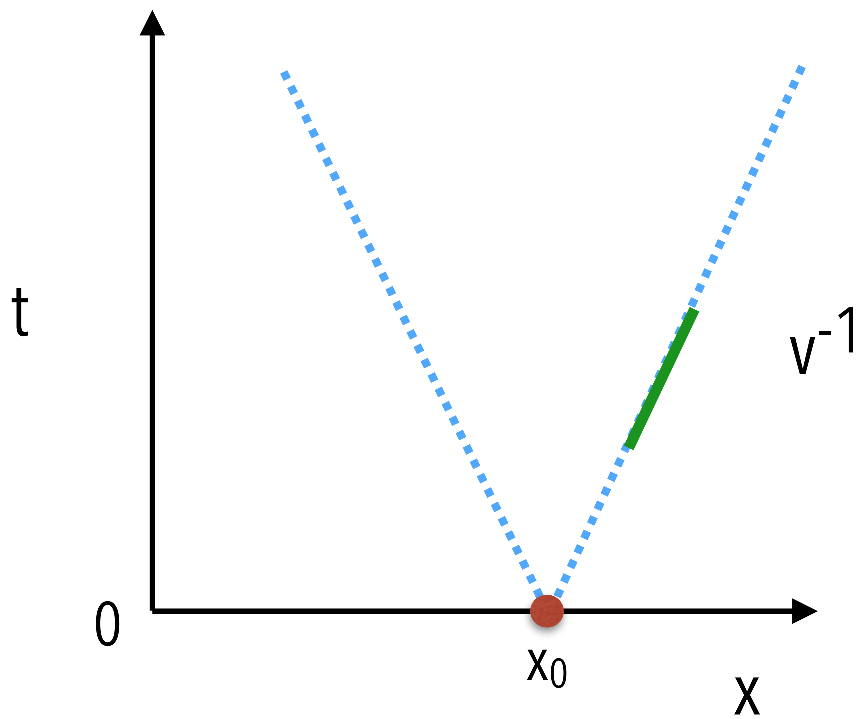
No driving

$$\langle\phi(x,t)\phi(0,0)\rangle \propto \frac{1}{(x-t)^2}\frac{1}{(x+t)^2}$$



Dubail et al

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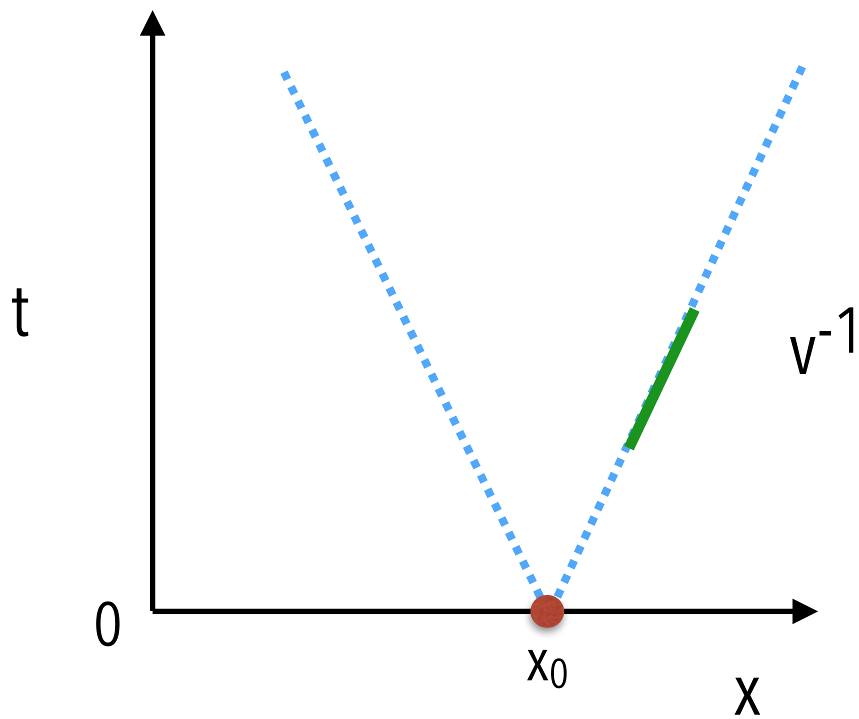
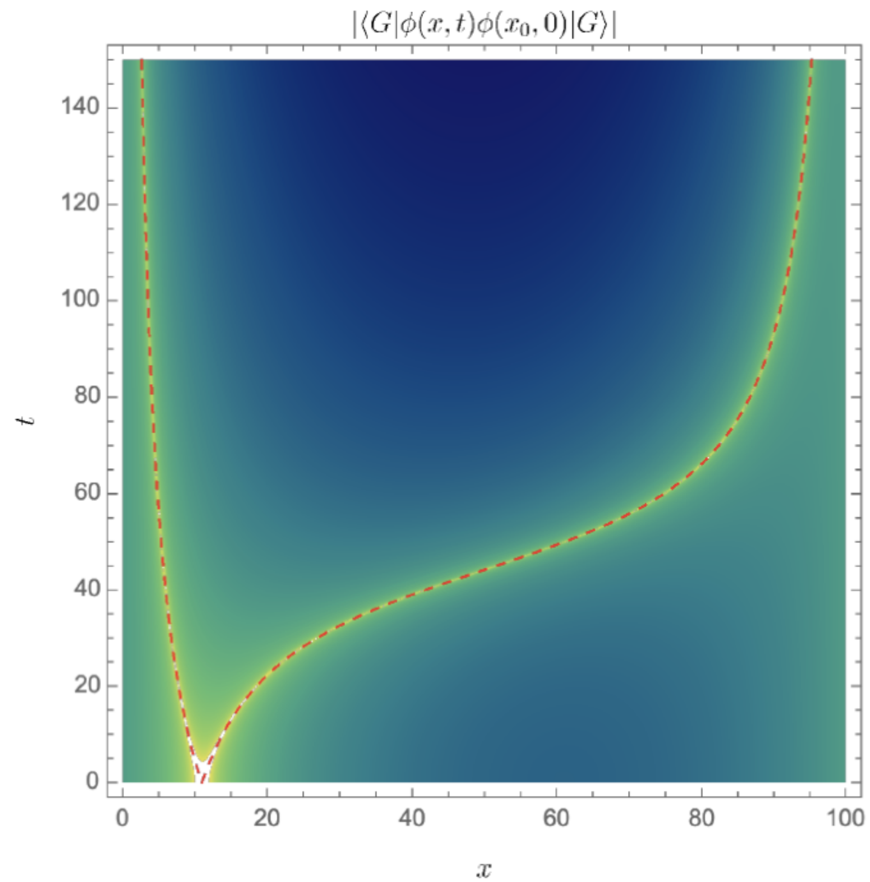


SSD



$$\langle\phi(x,t)\phi(0,0)\rangle \propto \frac{1}{(x-v(x)t)^2}\frac{1}{(x+v(x)t)^2}$$

Dubail et al

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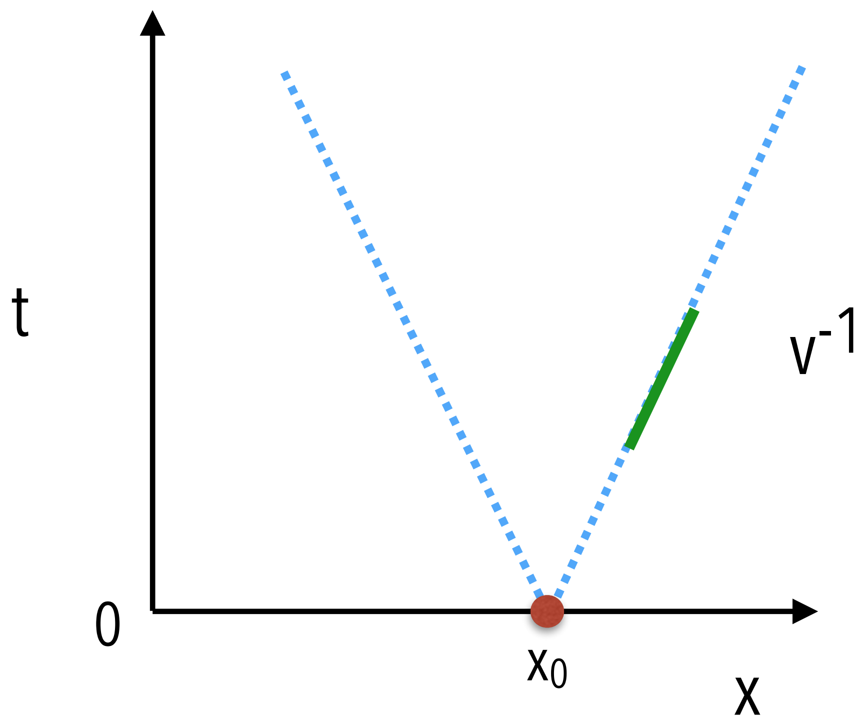

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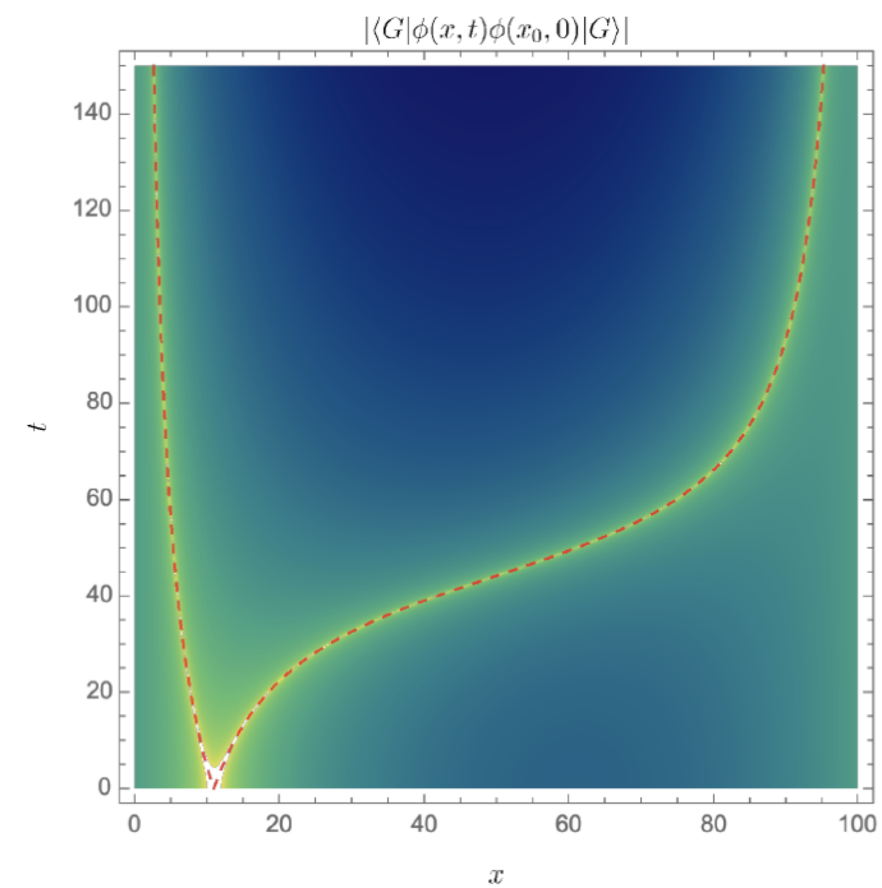


$$\langle \phi(x,t)\phi(0,0)\rangle \propto \frac{1}{(x-v(x)t)^2}\frac{1}{(x+v(x)t)^2}$$

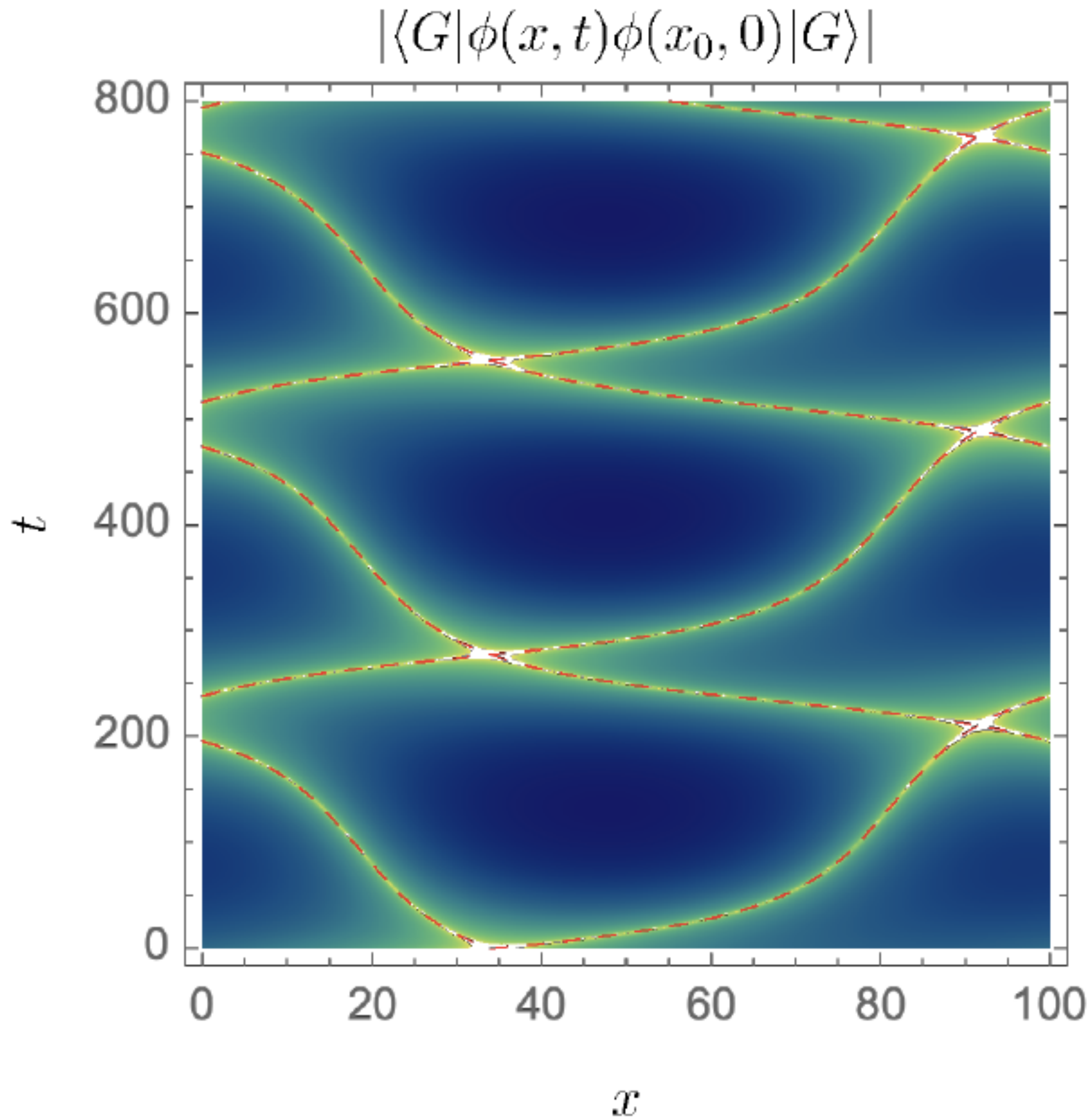
Excitations propagate in curved space

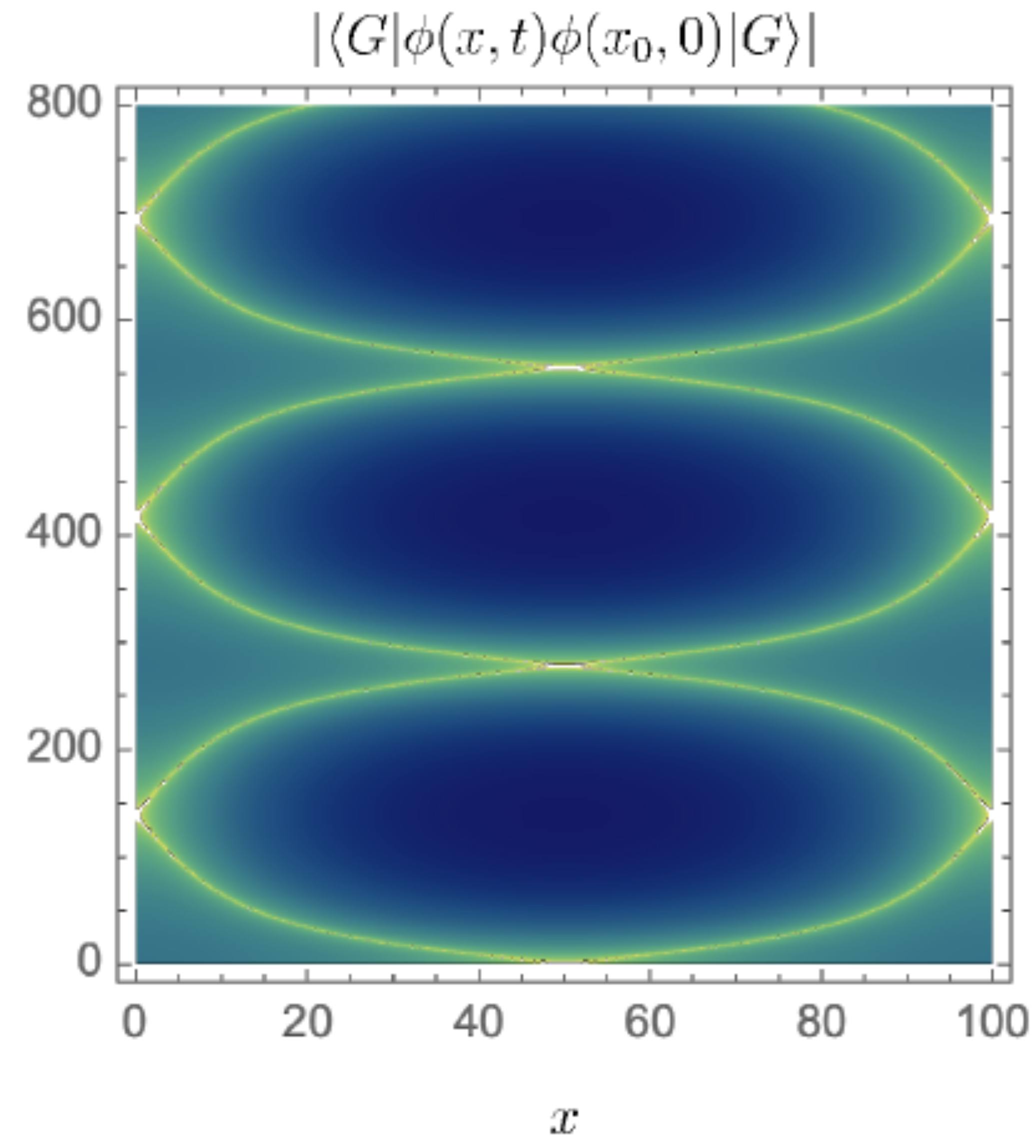
$$ds^2 = dx^2 - \left(2\sin^2\left(\frac{\pi x}{L}\right)\right)^2 dt^2$$

Dubail et al

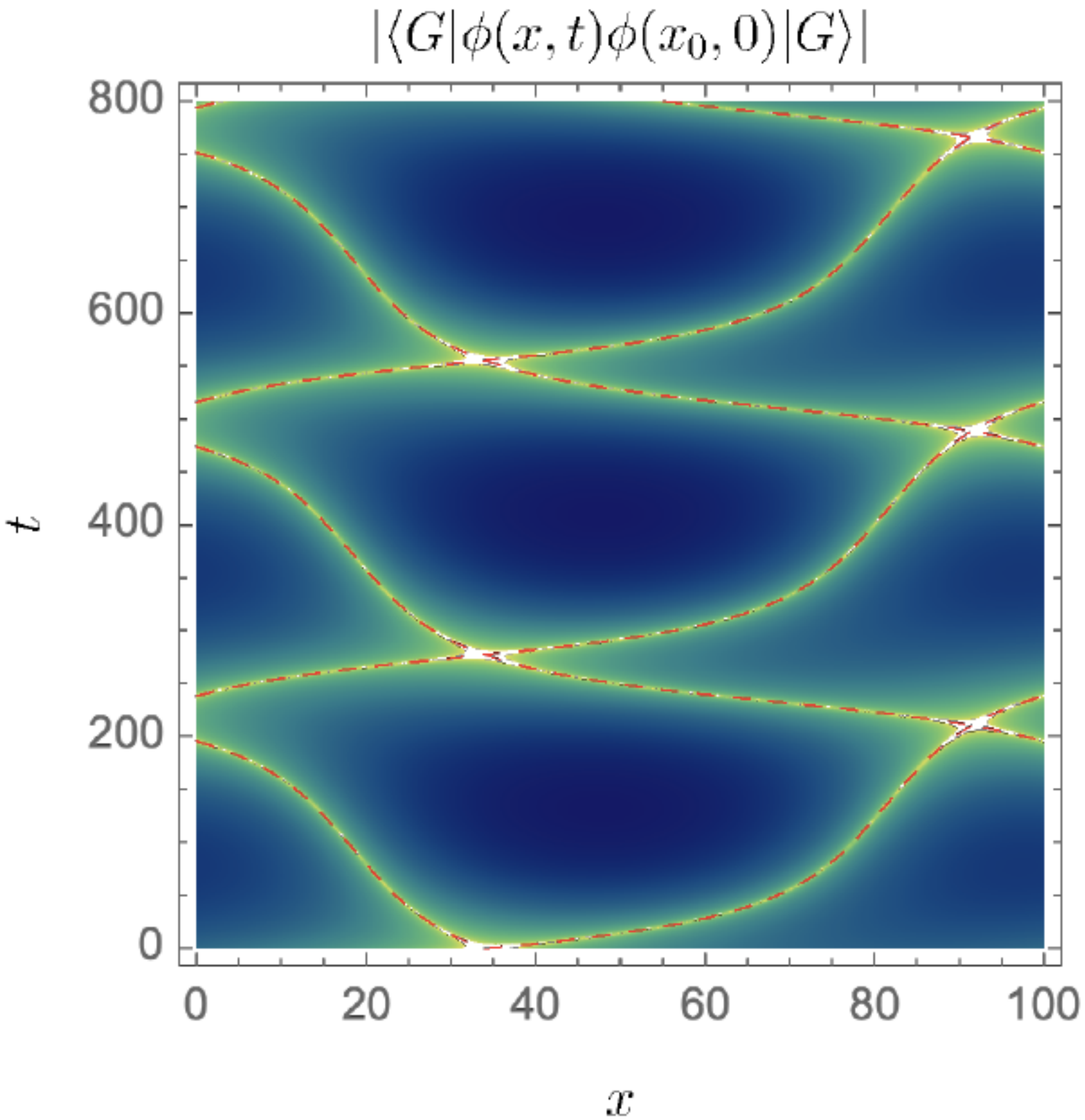
Non-heating phase

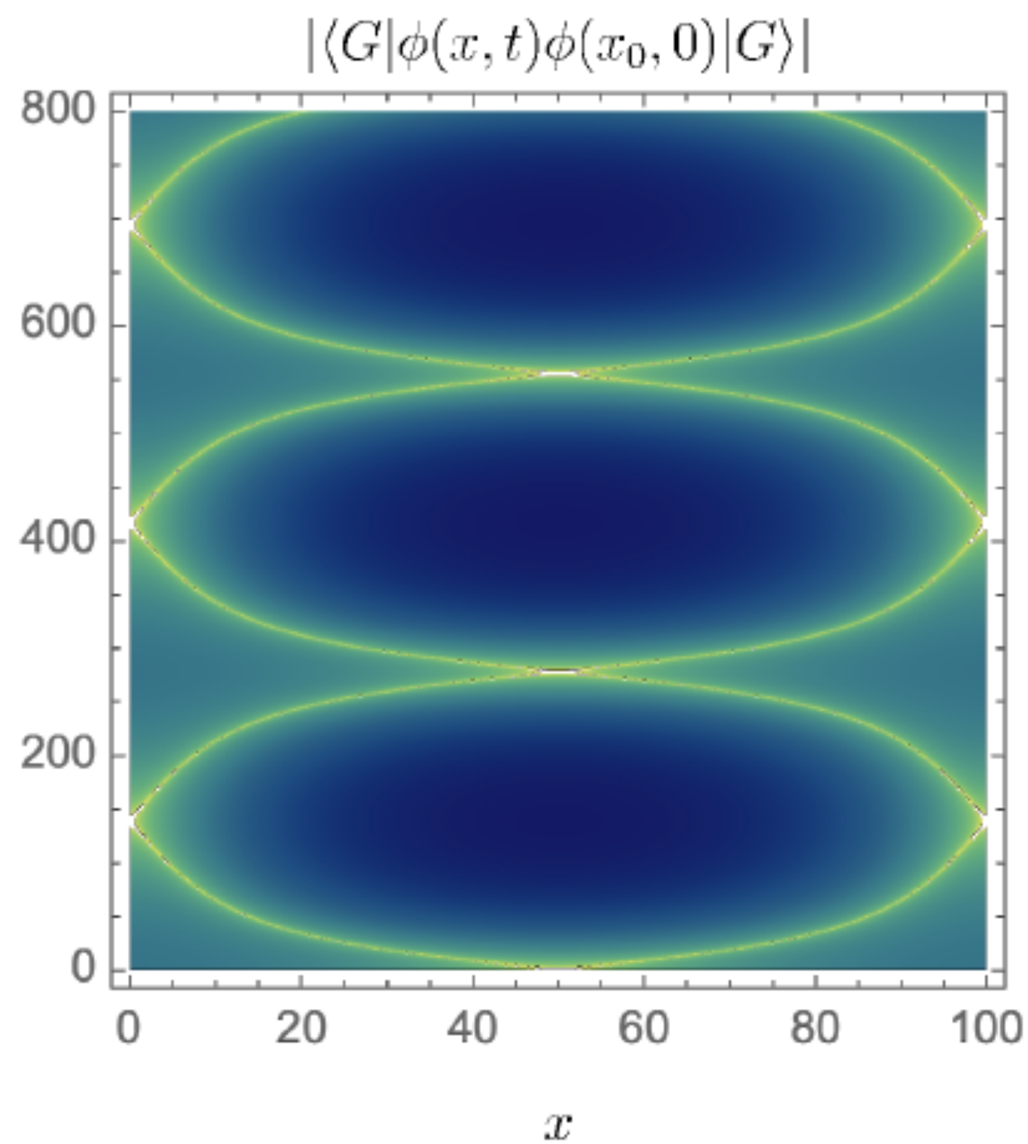
Non-heating phase





Non-heating phase

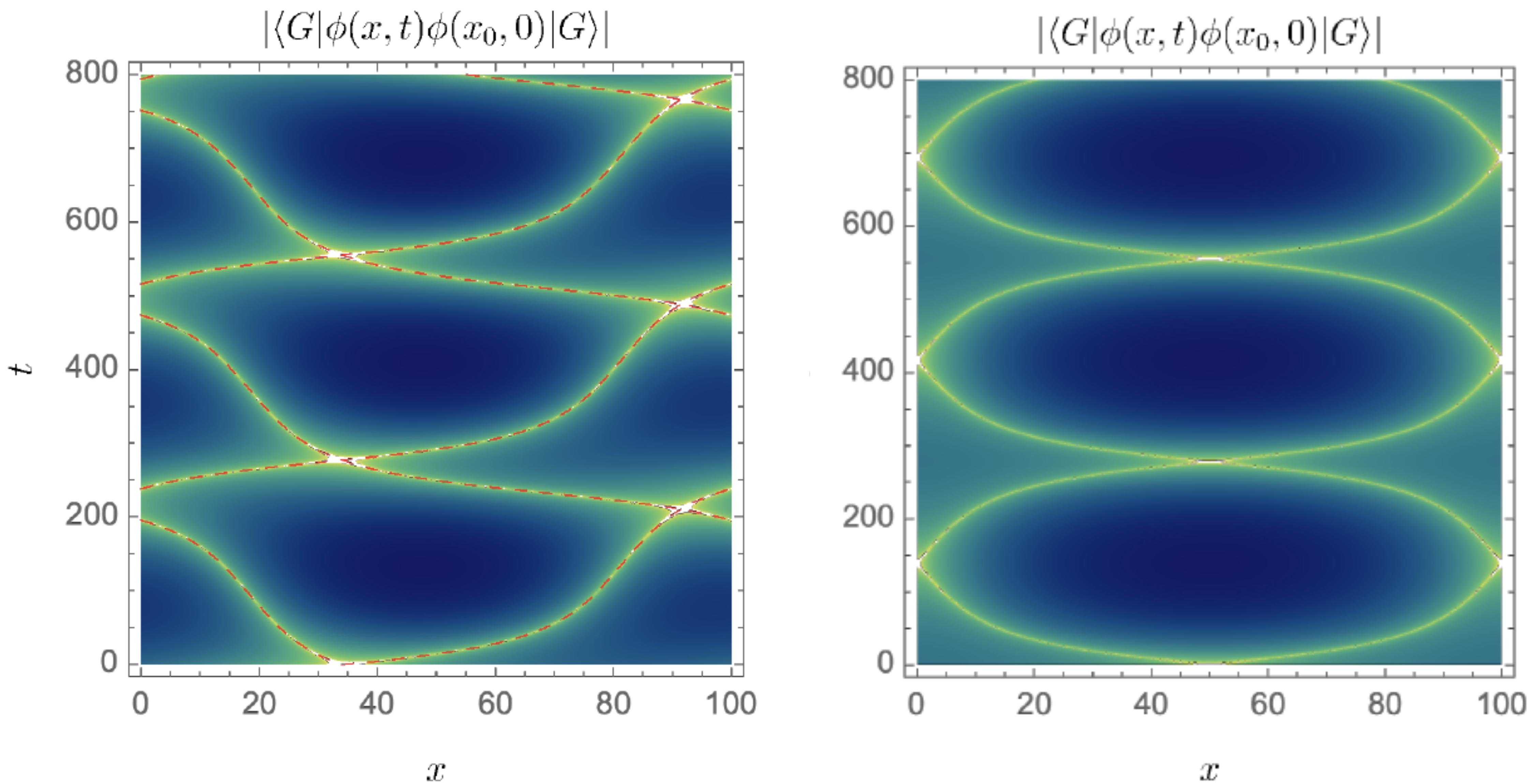




Emergent period

$$T_E = 2\pi \frac{T_0+T_1}{|\log(\eta)|}$$

Non-heating phase



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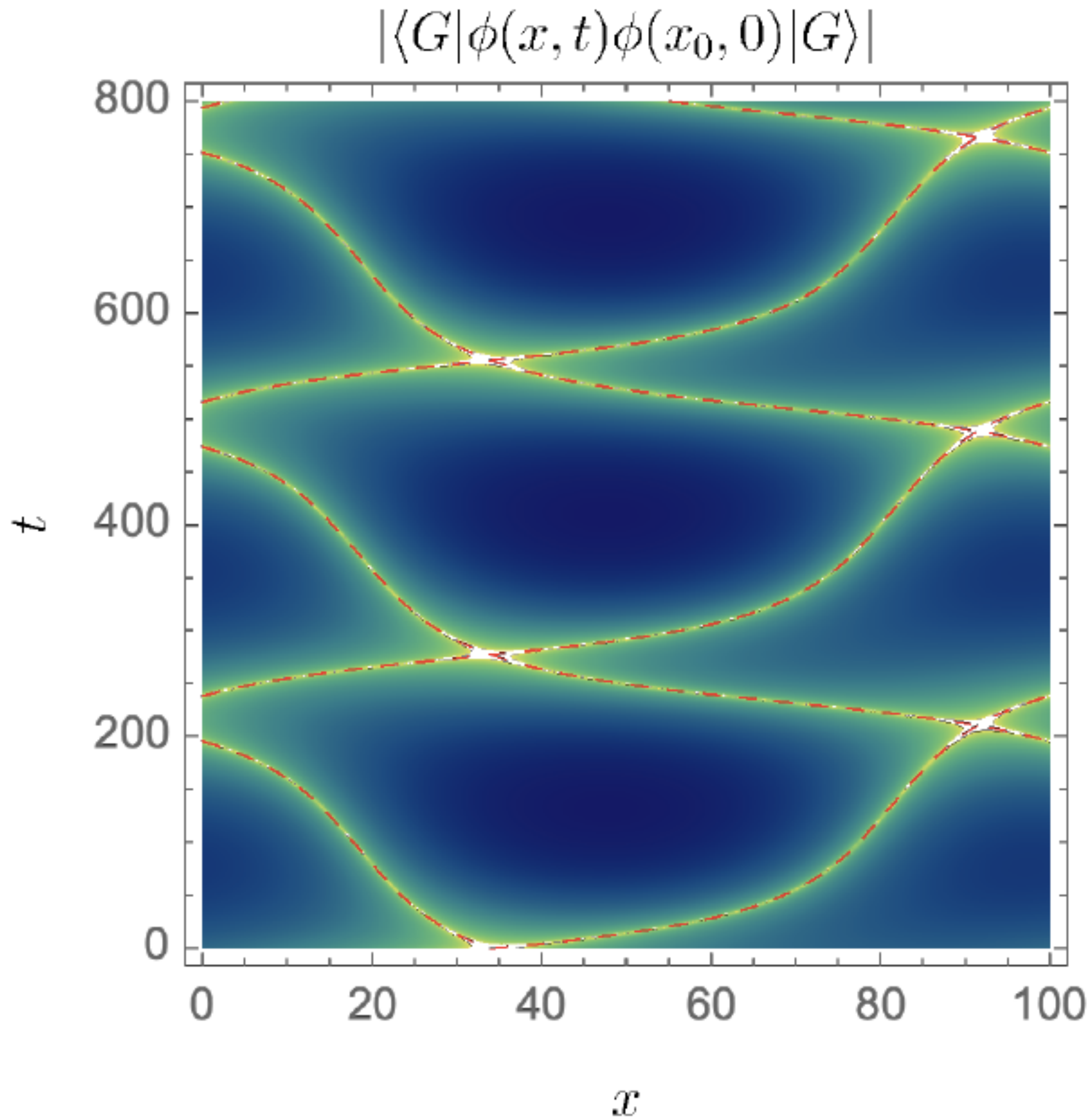
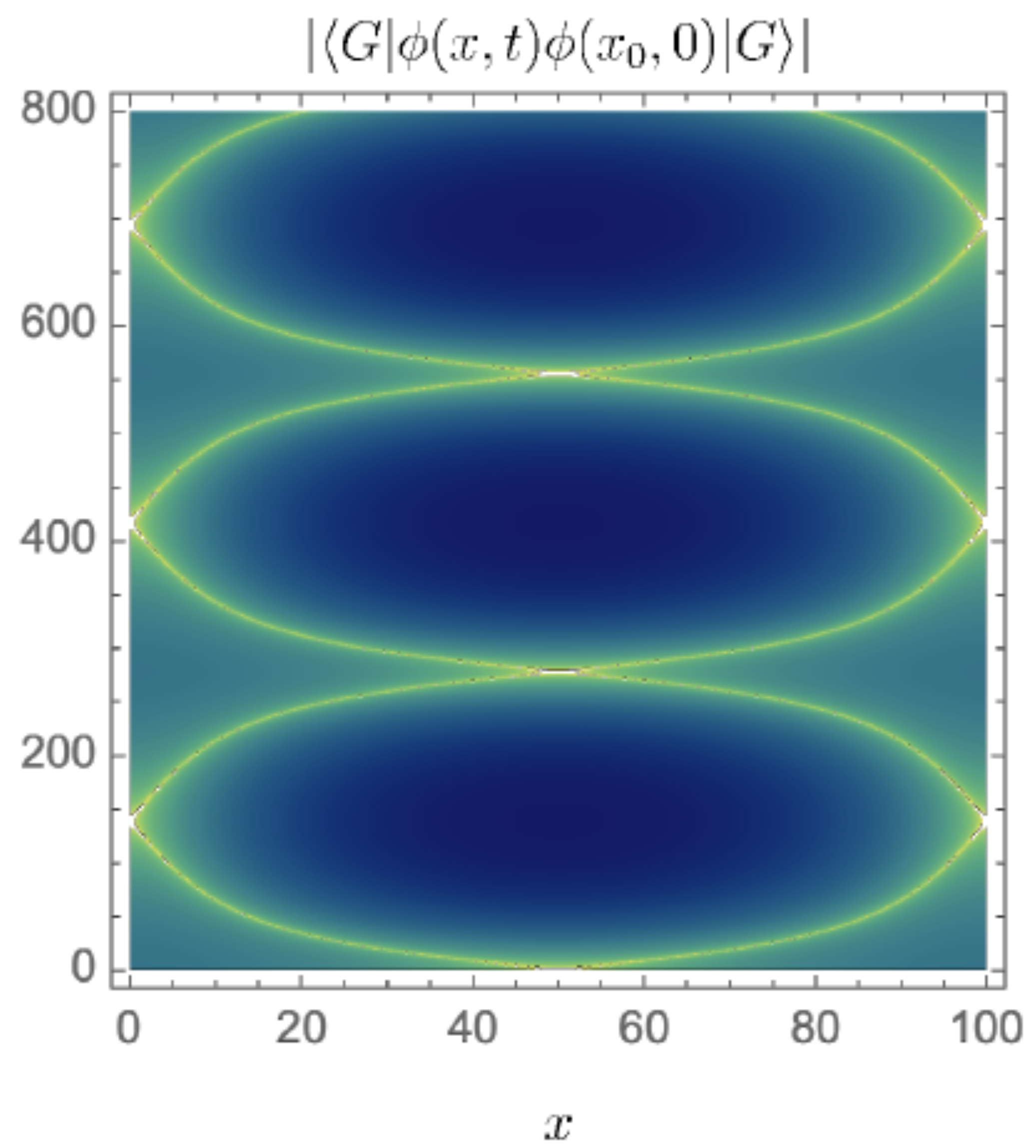
Non-heating phase





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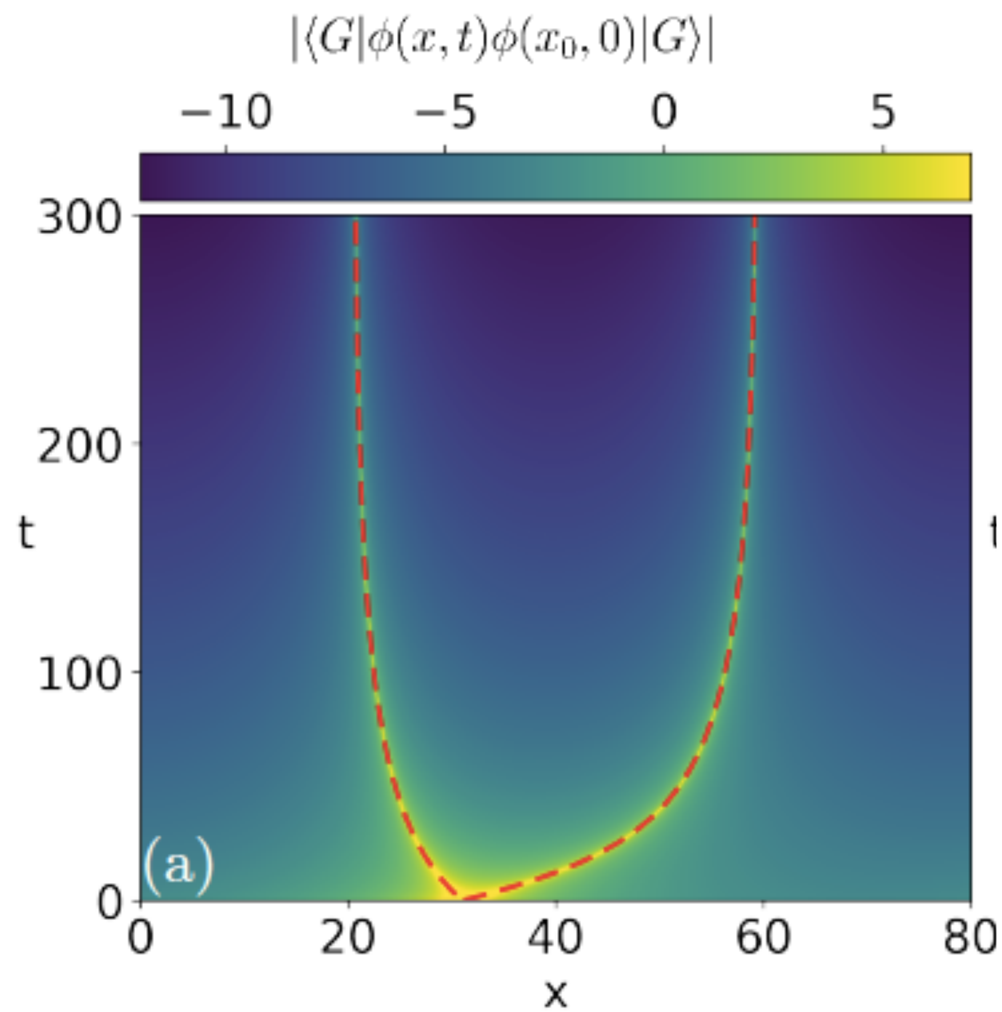
$$T_E = 2\pi\frac{T_0+T_1}{|\log(\eta)|}$$

Geodesics $ds^2 = dx^2 - f(x)dt^2$

$T_E \to \infty$ at phase boundary

Heating Phase: a tale of black holes



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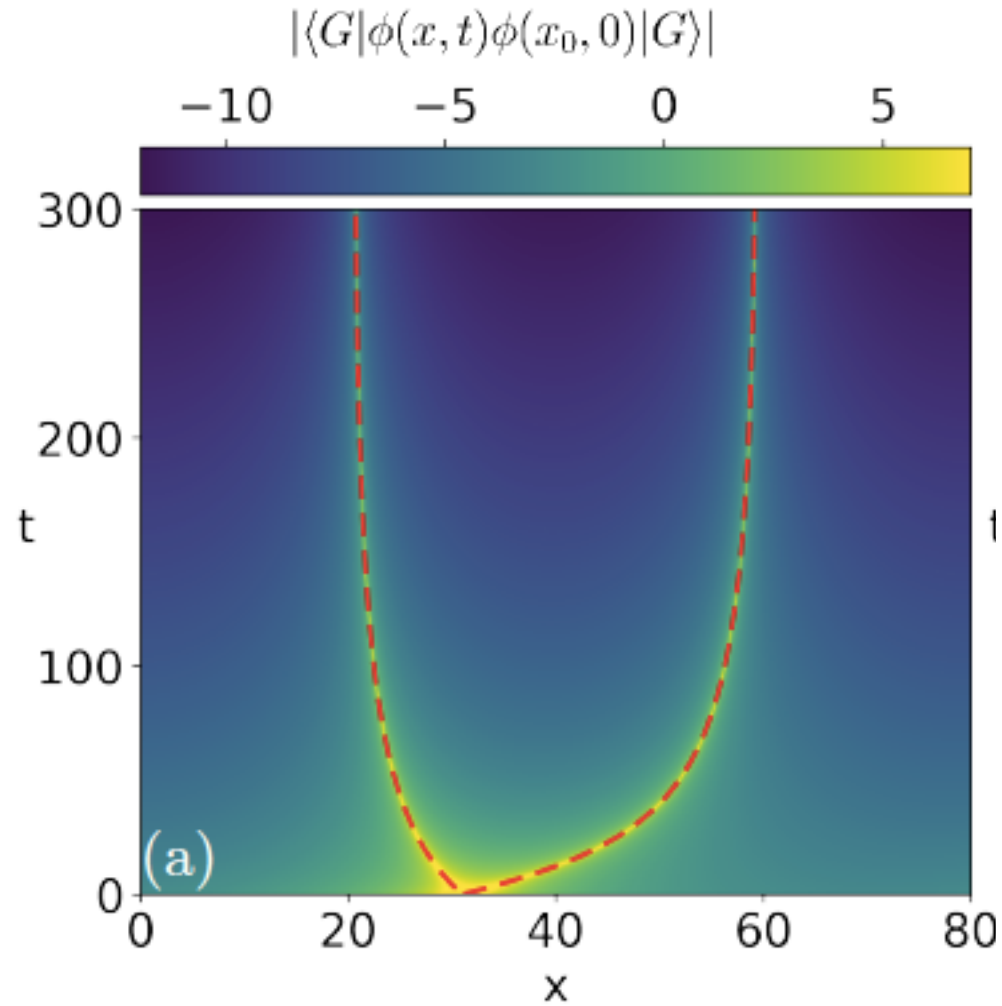

Rindler (black hole) metric

$$ds^2 = -\Theta_H^2 (x - x_c)^2 dt^2 + dx^2$$

$$ds^2 = -\Theta_H^2 (x - (L - x_c))^2 dt^2 + dx^2$$

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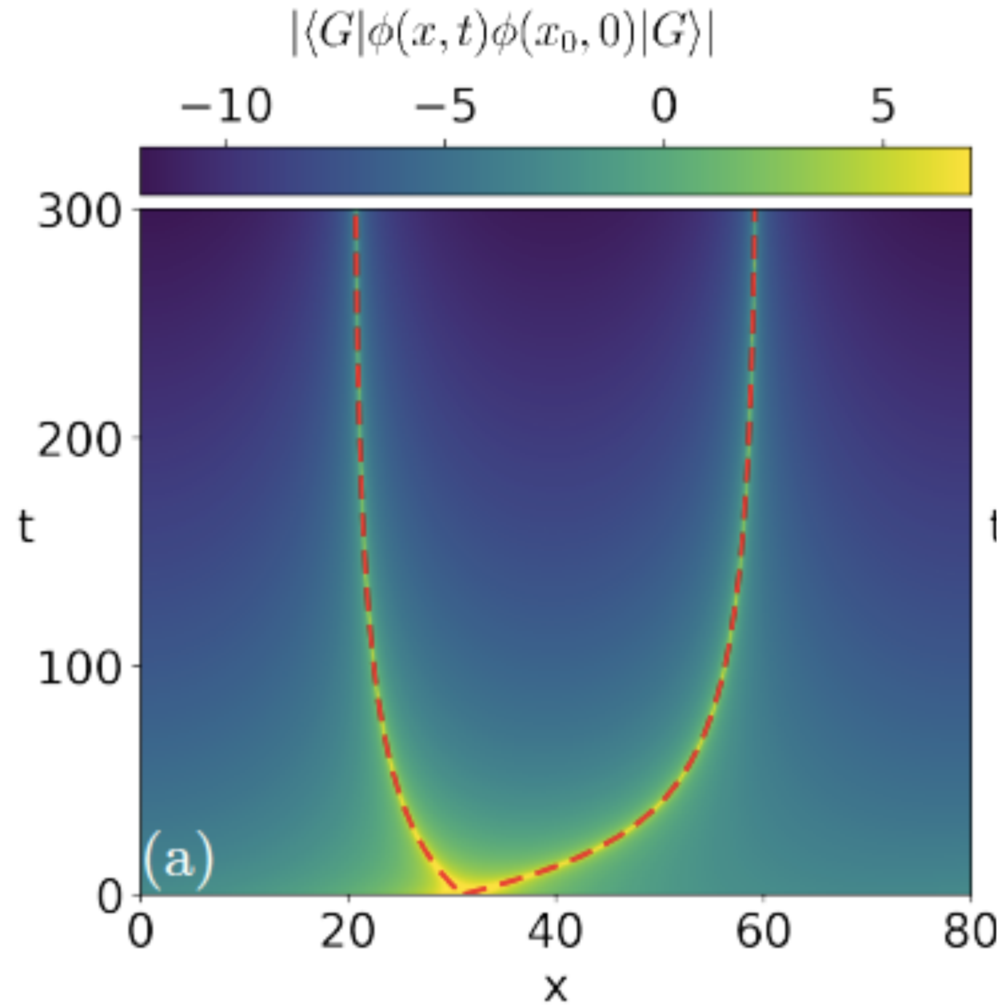

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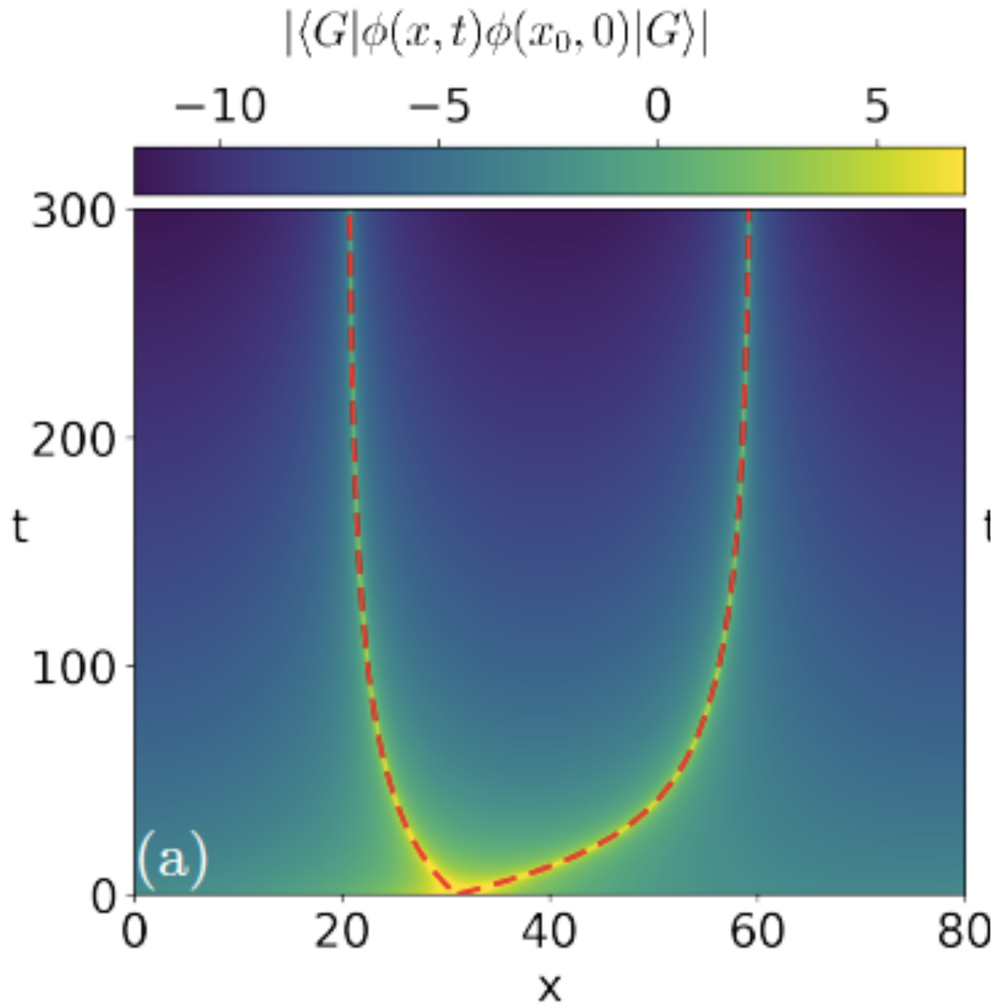

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Excitations stuck between the two horizons

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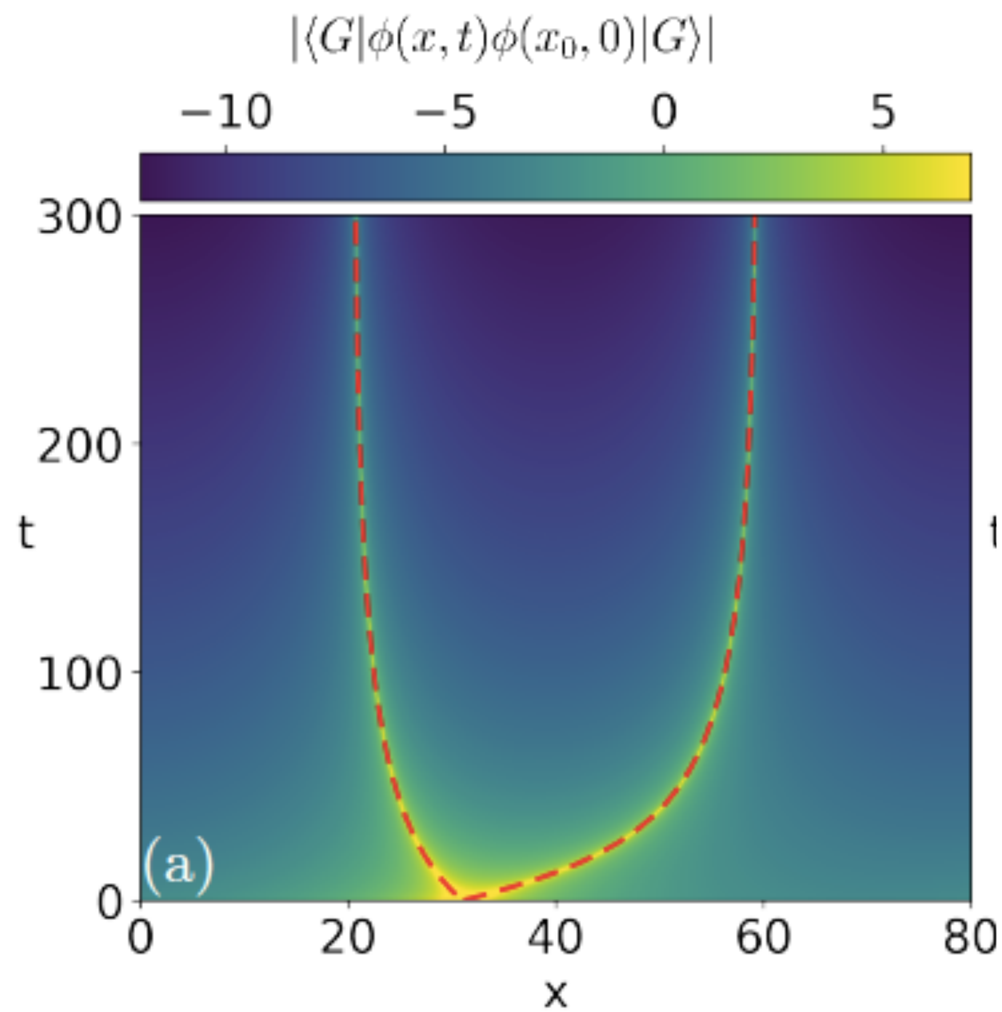

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Excitations stuck between the two horizons

Hawking temperature $\Theta_{\mathrm{H}} = \dfrac{|\log(\eta)|}{2\pi(T_0 + T_1)}$

How does the system heat up ?

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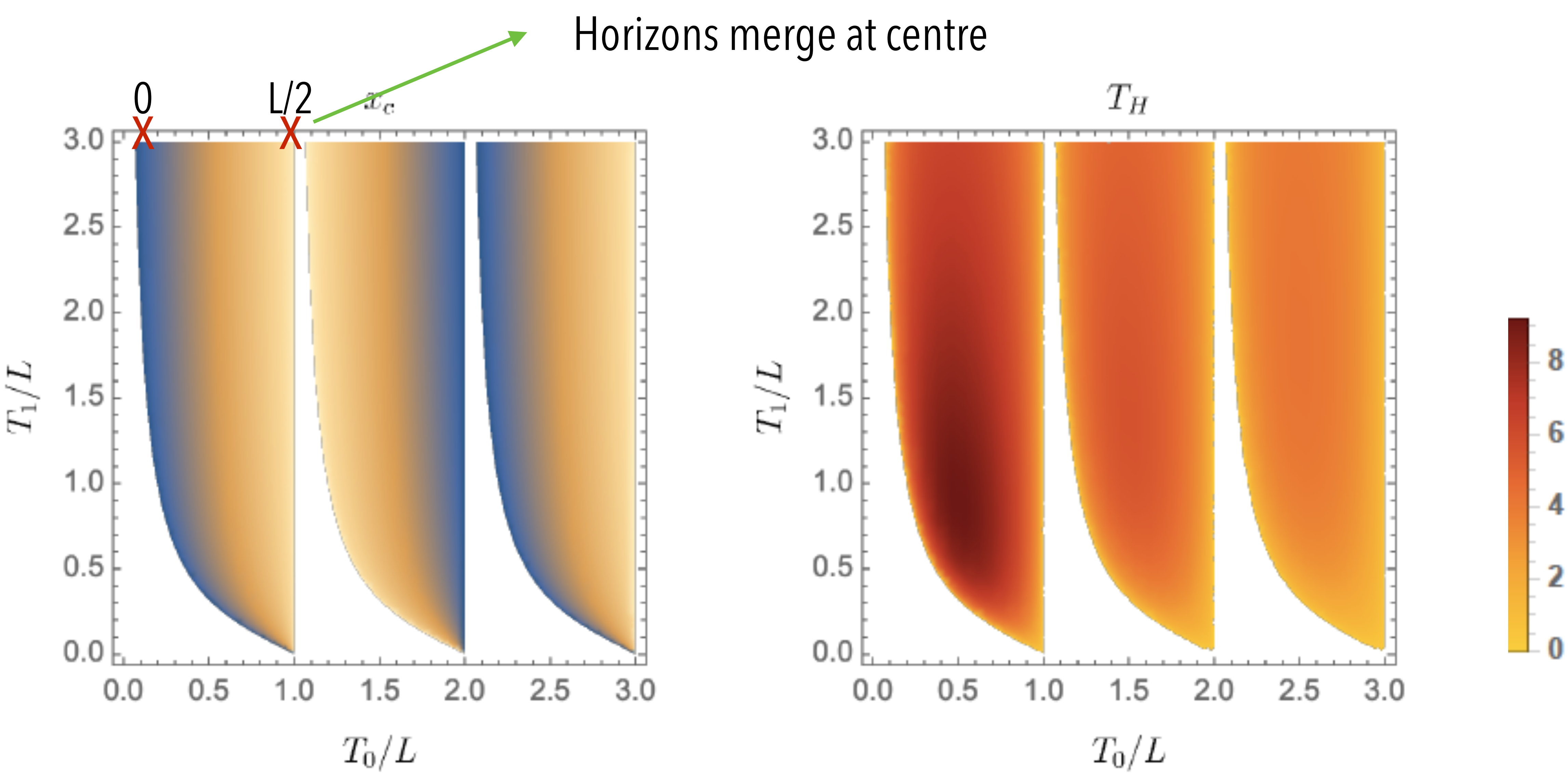
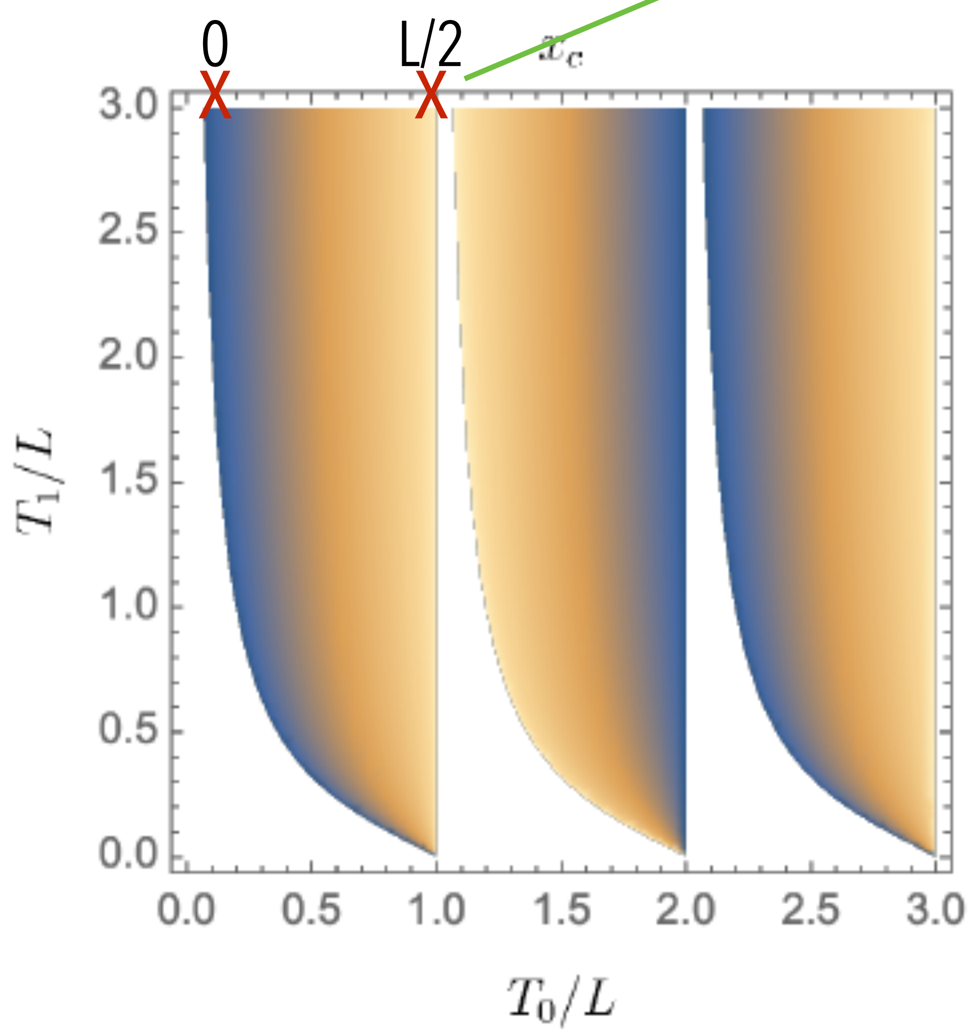
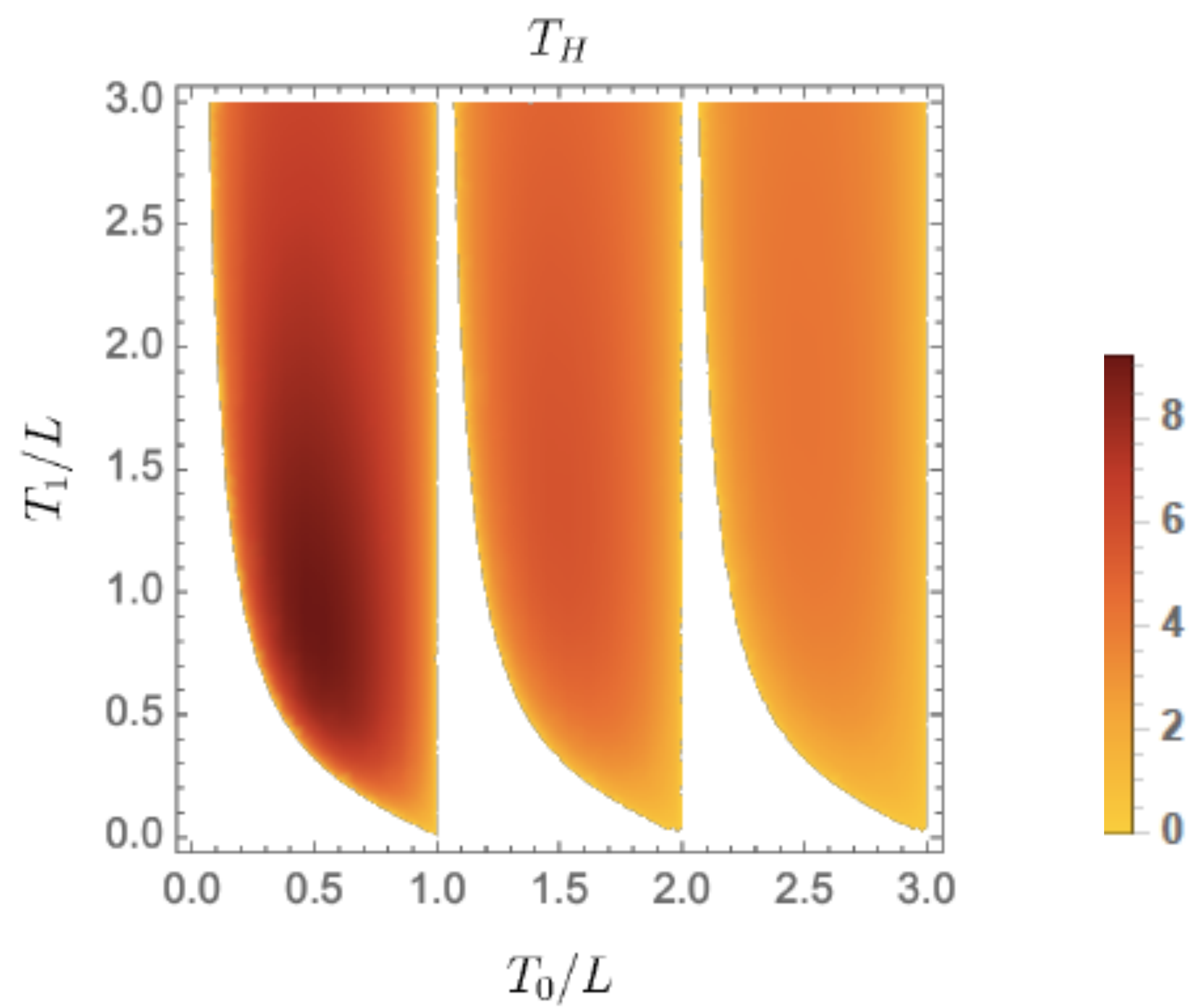


How does the system heat up ?

Horizons merge at centre





Effective local temperature

$$\beta_{\text{eff}}(x) = \Theta_H \frac{\sin\left(\frac{\pi}{L}(x - x_c)\right)\sin\left(\frac{\pi}{L}(x + x_c)\right)}{\sin\left(\frac{2\pi x_c}{L}\right)}$$

Cardy & Tonni, 2016

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Lattice systems - XXZ spin chain

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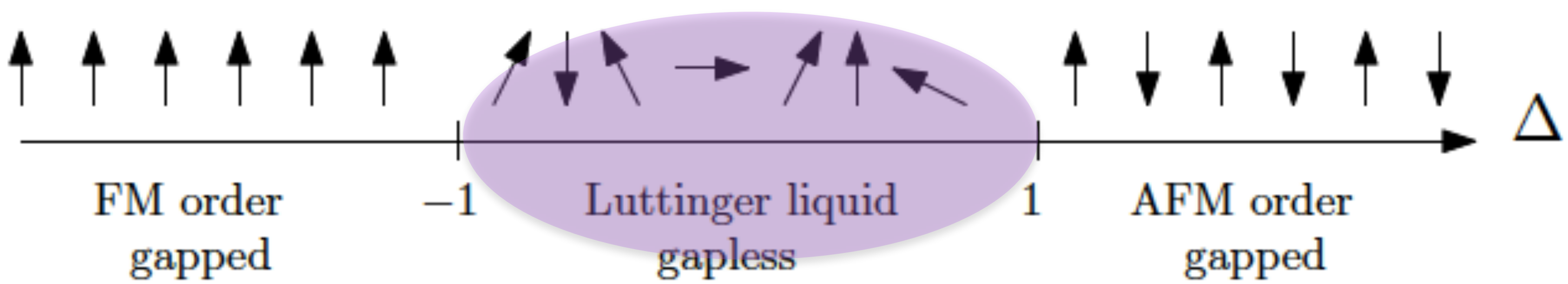
$$H = J \sum_{j=1}^{L-1} f_j \Big(S_j^x S_{j+1}^x + S_j^y S_{j+1}^y + \Delta S_j^z S_{j+1}^z \Big)$$



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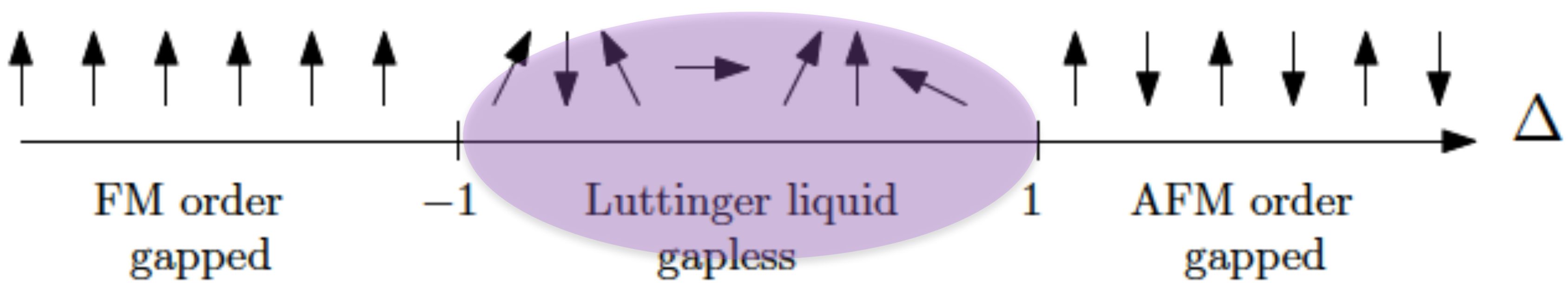

$$H = \frac{u}{2\pi} \int_0^L \left[K \Pi^2 + \frac{1}{K} (\partial_x \phi)^2 \right]$$

CFT c=1, compact boson field

MPS simulations Gapless Phase

MPS simulations Gapless Phase

Evolve with $U(t) = \underbrace{e^{-iT_0 H_{XXZ}} e^{-iT_1 H_{SSD}} \ldots e^{-iT_0 H_{XXZ}} e^{-iT_1 H_{SSD}}}_{\text{N times}}$

Compute $\langle G | S_z(x,t) S_z(x_0,0) | G \rangle$

MPS simulations   Gapless Phase

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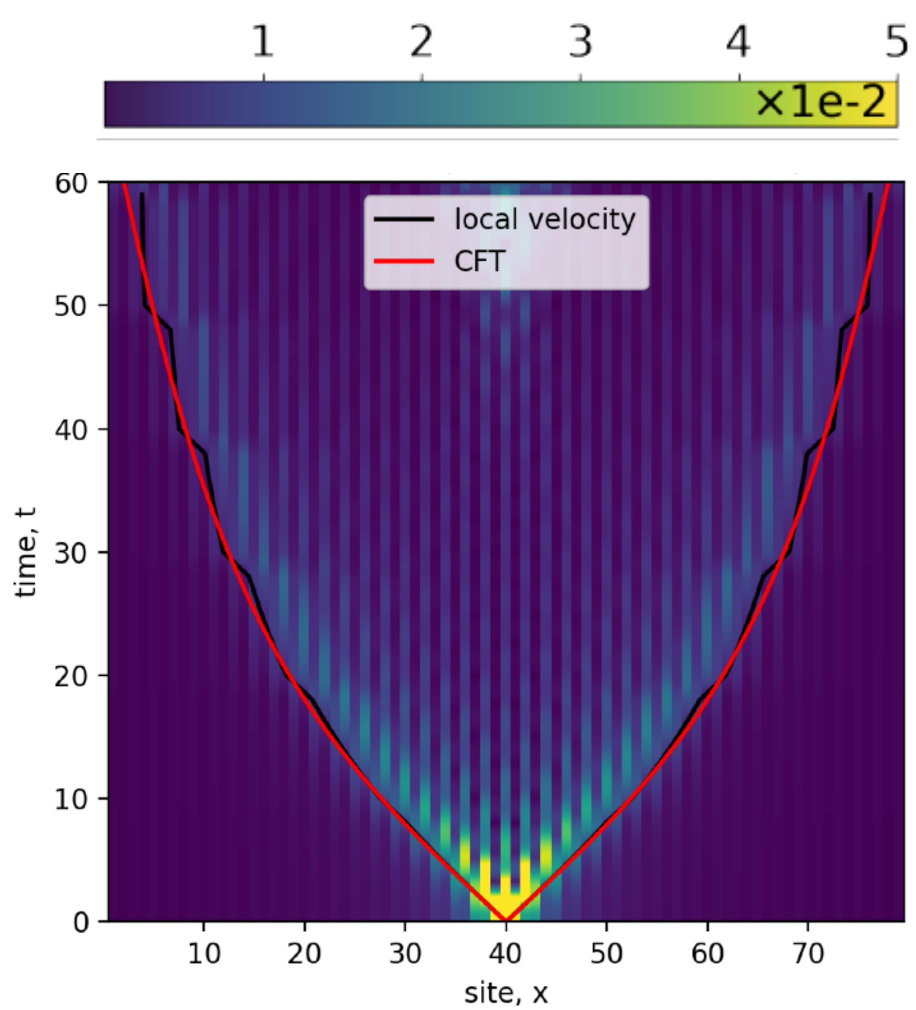
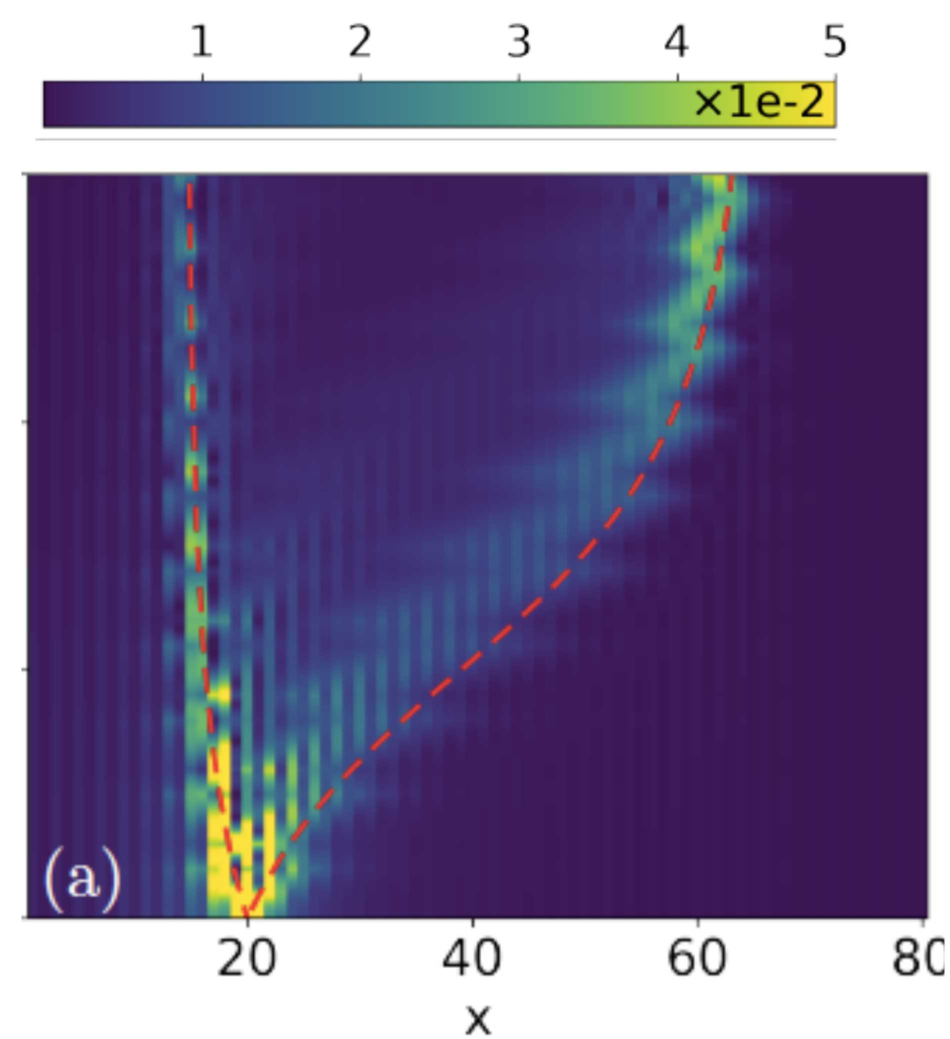


T0 = 2, T1 = 8
(Non-Heating)



T0 = -2, T1 = 8
(Heating)

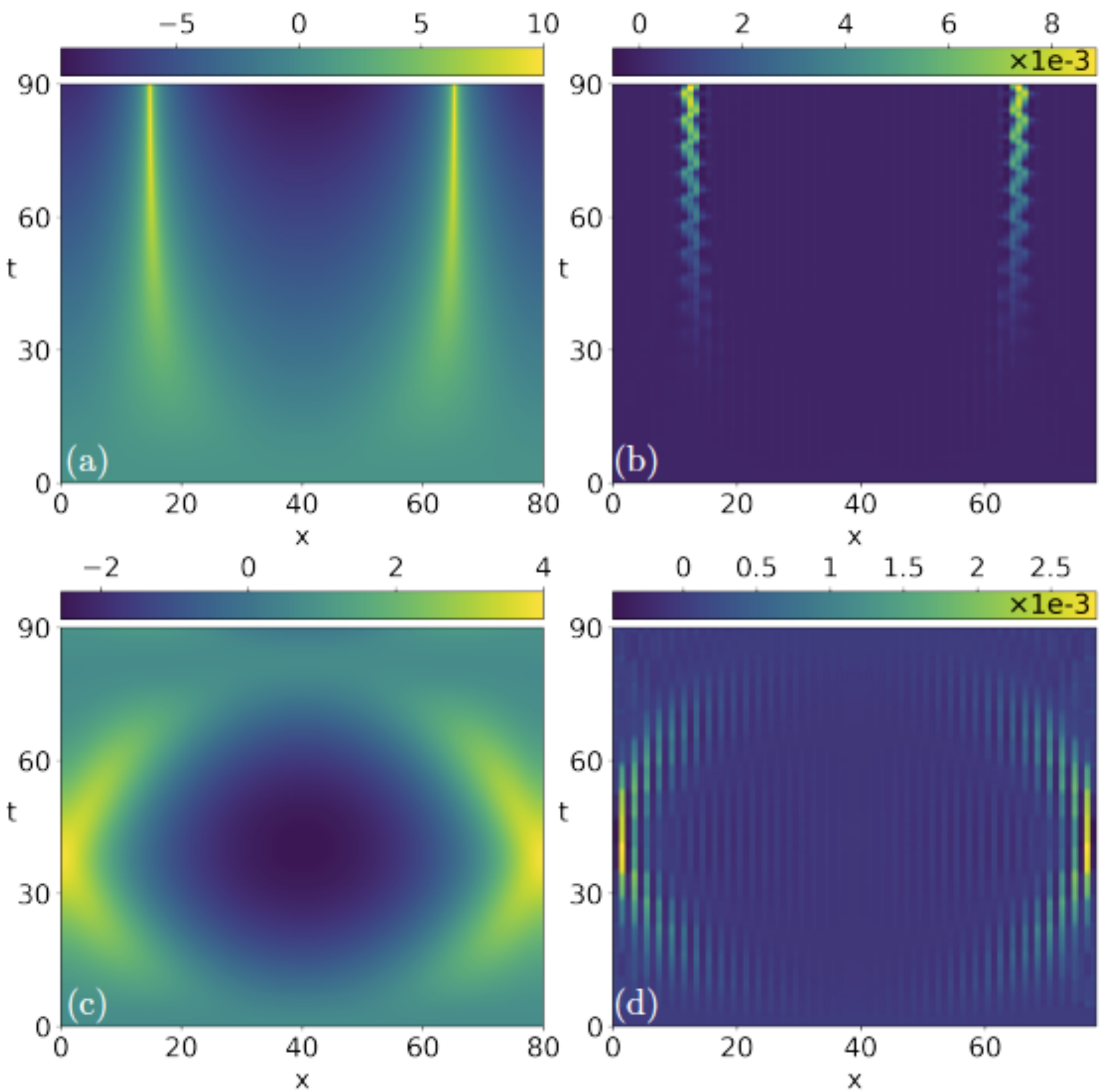
Energy absorption

$$\epsilon(x,t) = \langle \psi(t) | T_{00}(x) | \psi(t) \rangle$$

CFT c=1 XXZ chain

Heating

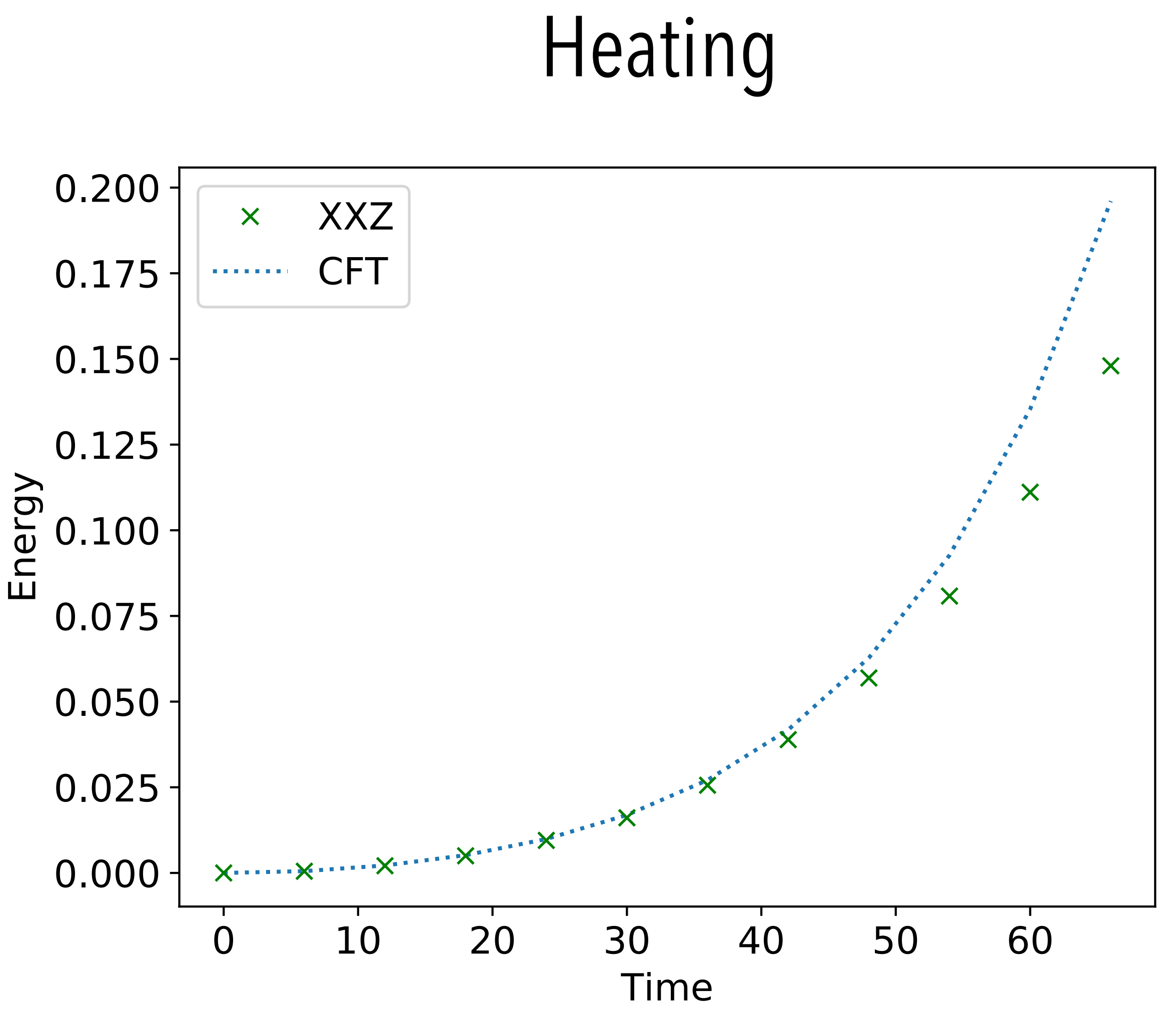
Non-heating

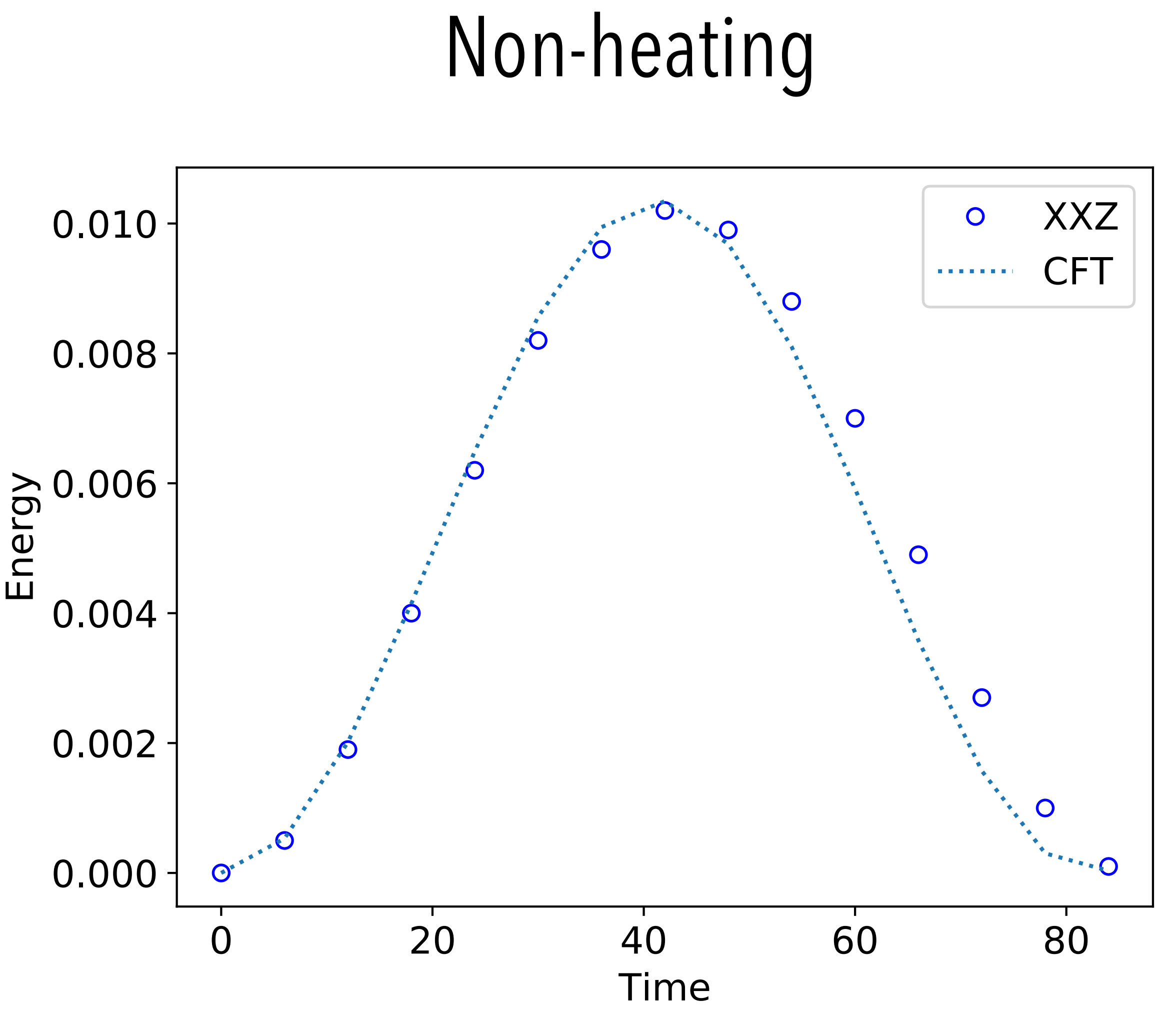


Accumulation of energy - black hole singularities

Energy density oscillates with period T_E

Comparison lattice model and CFT





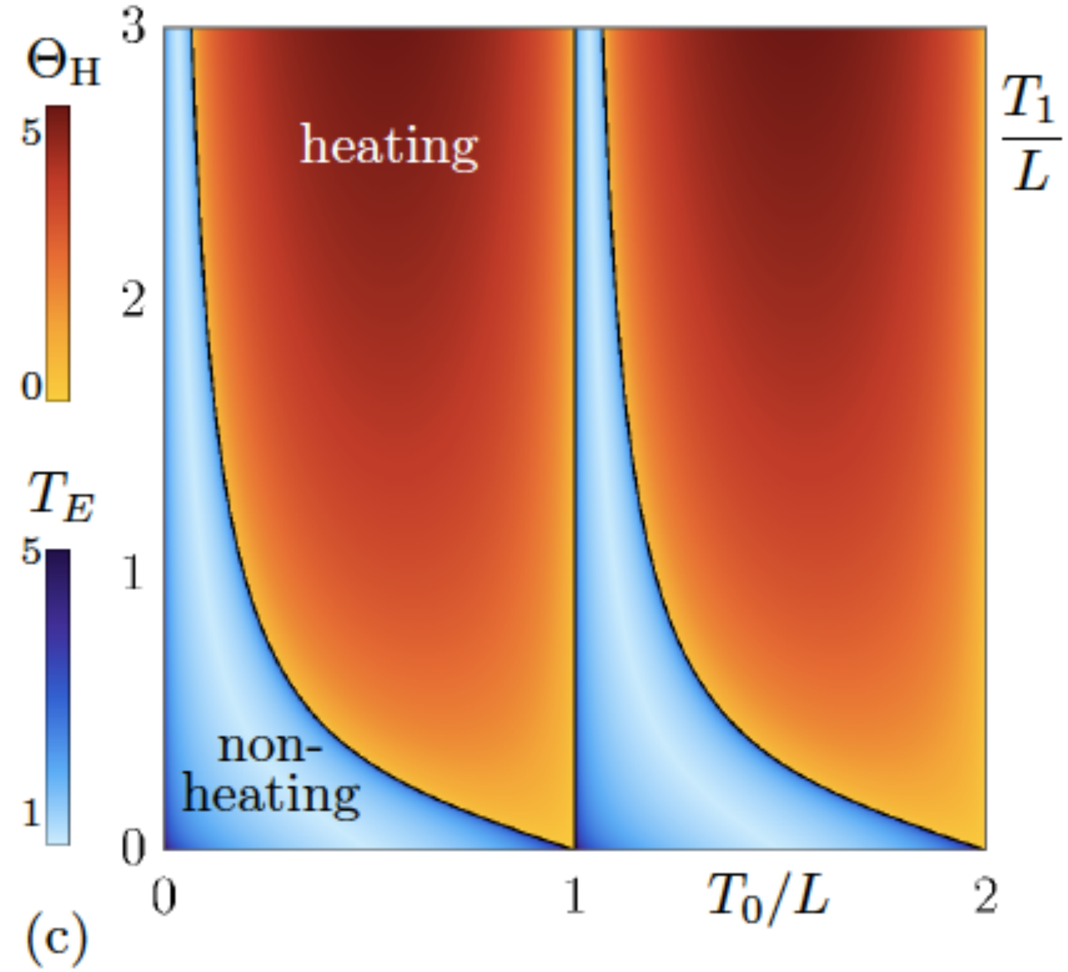
Summary

SSD Hamiltonians with periodic driving shows transition between heating and non-heating phase

heating in ‘hot spots’, comparably slow

excitations propagate analogous to curved space-time with black holes

picture valid beyond CFT, beyond periodic drive



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Electric-circuit realization of a hyperbolic drum

arxiv:2109.01148

with:

Ronny Thomale group, Würzburg

Tomas Bzdusek group, PSI Switzerland

Igor Boettcher, Alberta

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How to probe hyperbolic space?

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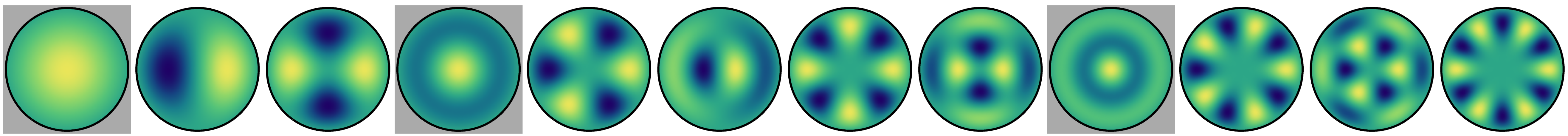
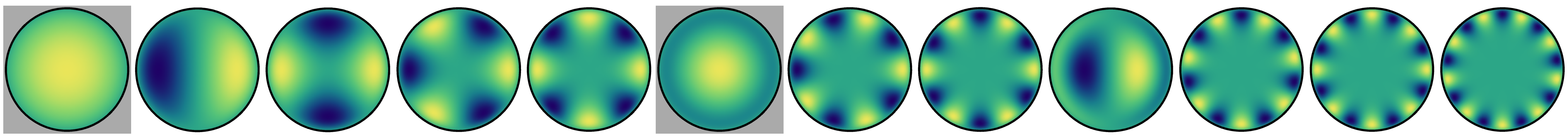
Energetic ordering of Laplacian eigenstates

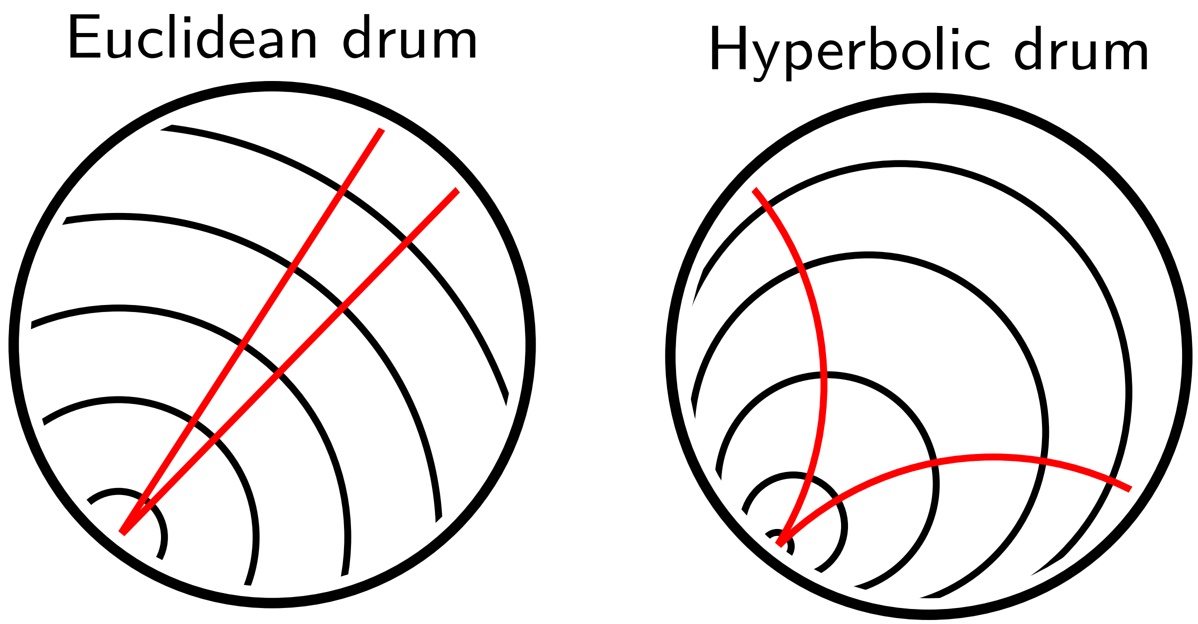
Euclidean drum



Hyperbolic drum



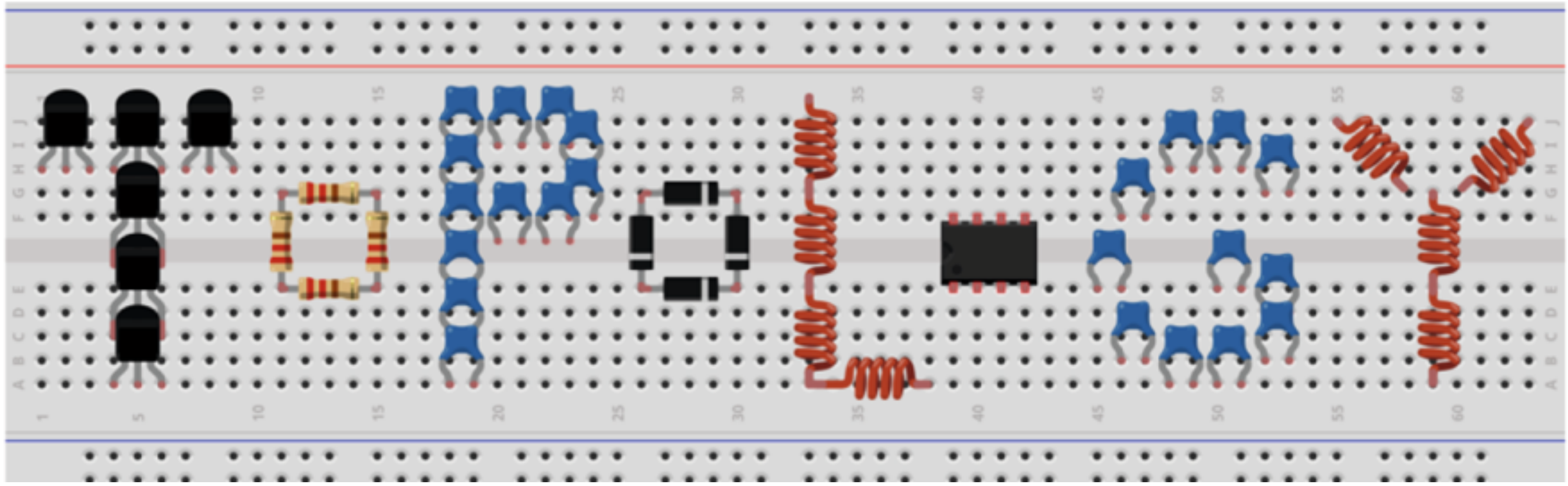
Geodesics



Experimental realization: Electric circuits

2+1D hyperbolic space cannot be embedded in 3+1D Euklidean space

Electrical circuits have loose locality constraint: circuit element instead of physical distance



[Ling Lu, Nature Physics (2018)]

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Electrical circuits have loose locality constraint: circuit element instead of physical distance

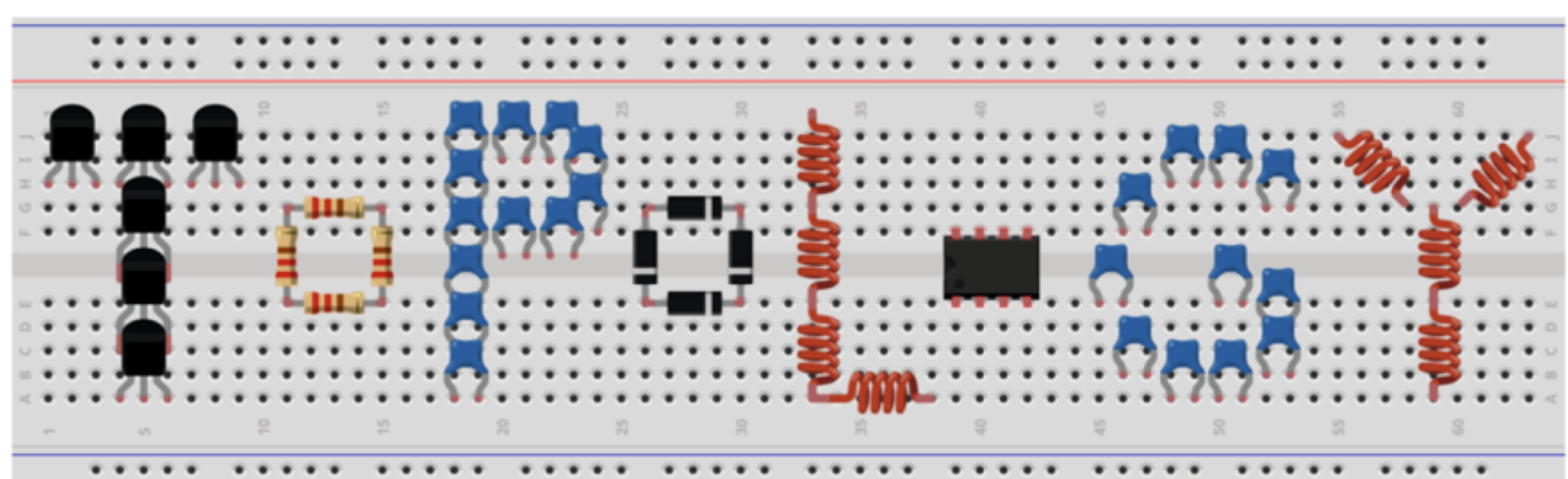
Kirchhoff's law

$$I_a(\omega) = \sum_{b=1,2,\cdots} J_{ab}(\omega)\, V_b(\omega)$$

circuit Laplacian

capacities inductances resistances

$$J_{ab}(\omega) = \mathrm{i}\omega C_{ab} - \frac{\mathrm{i}}{\omega\, L_{ab}} + \frac{1}{R_{ab}}$$



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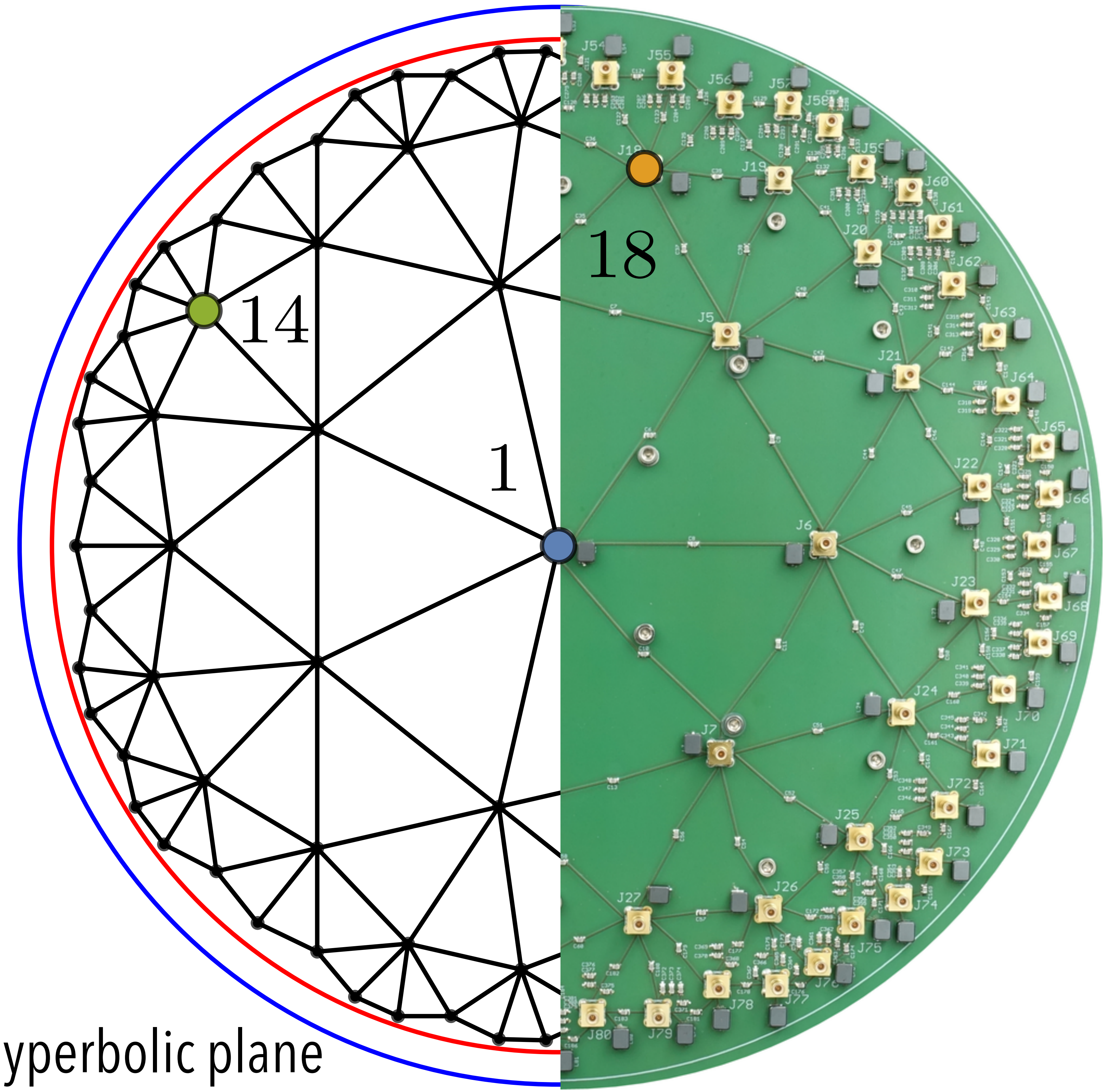
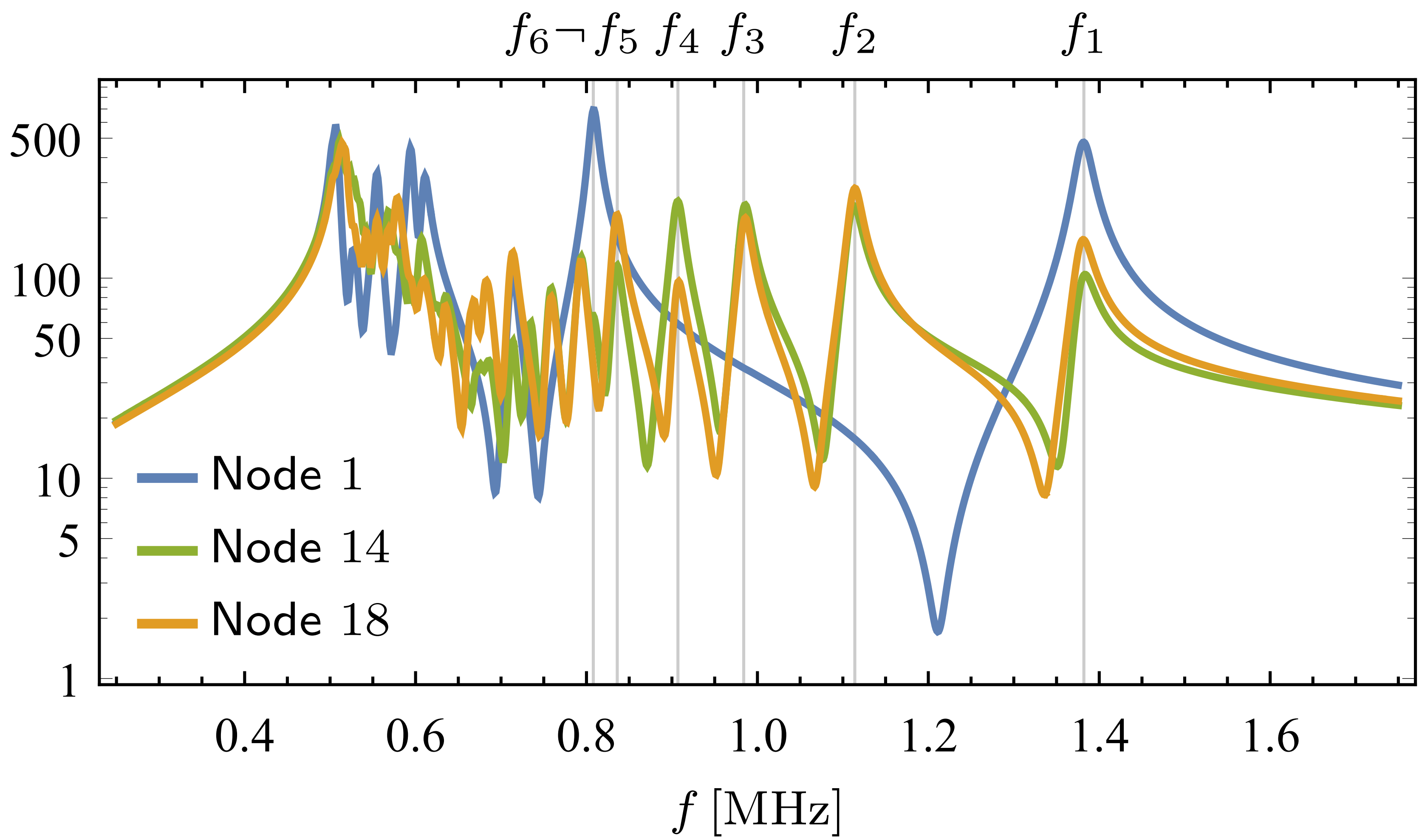
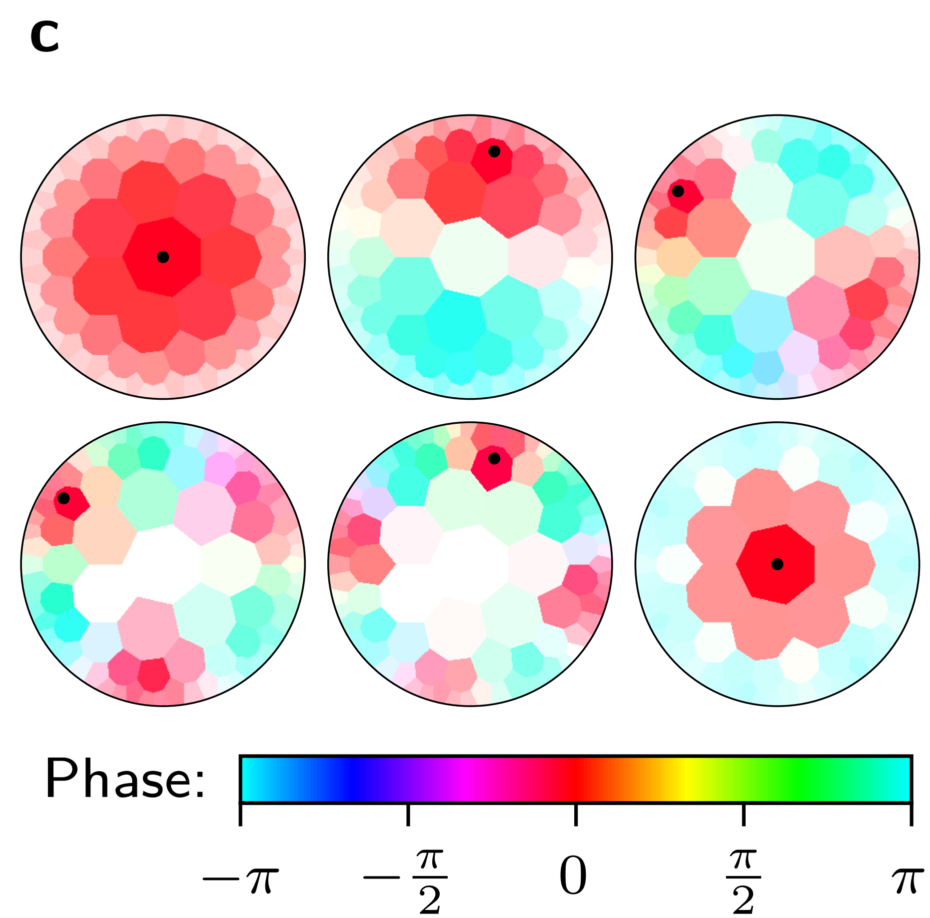
Hyperbolic circuit

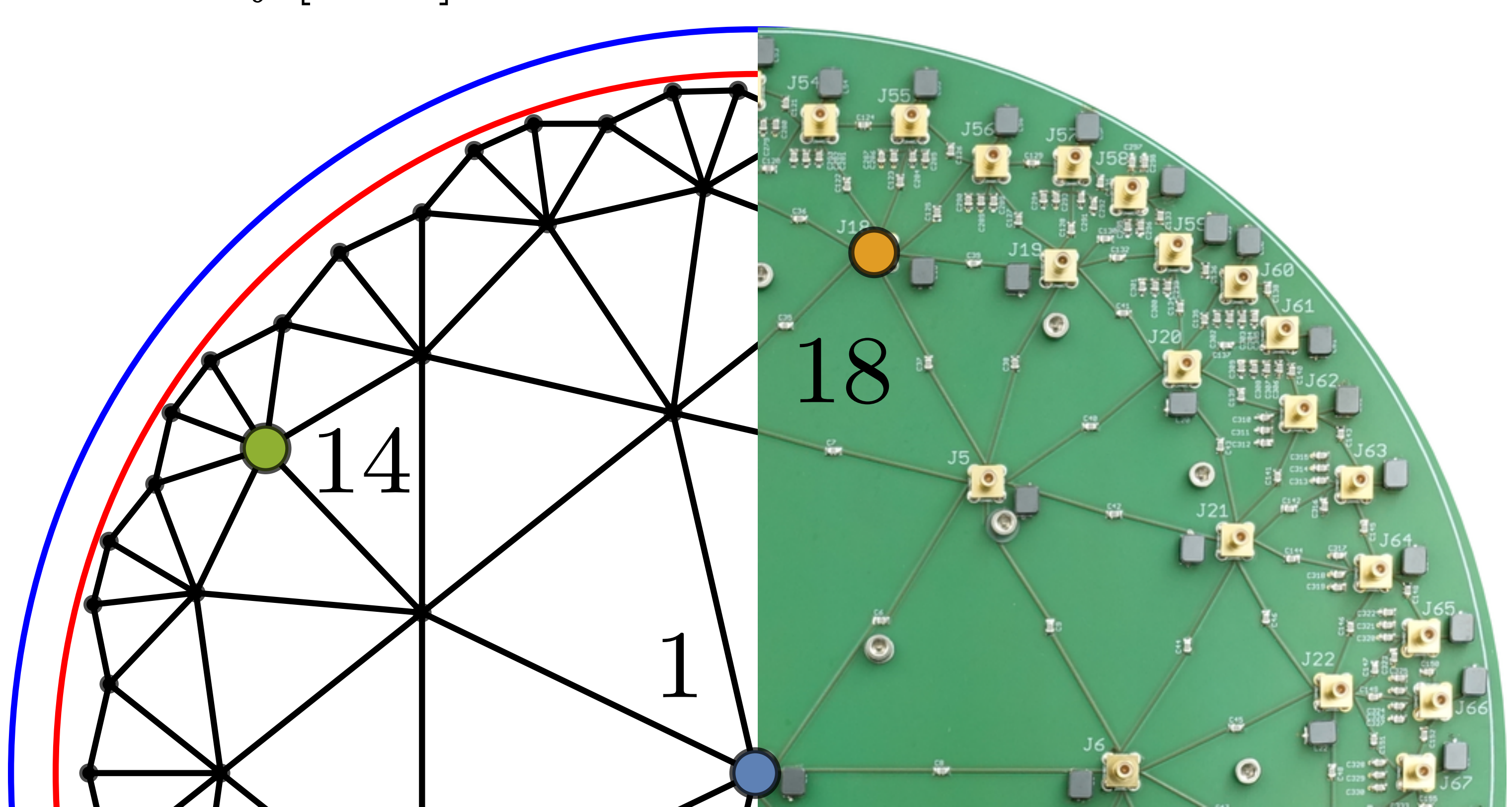


95% of hyperbolic plane

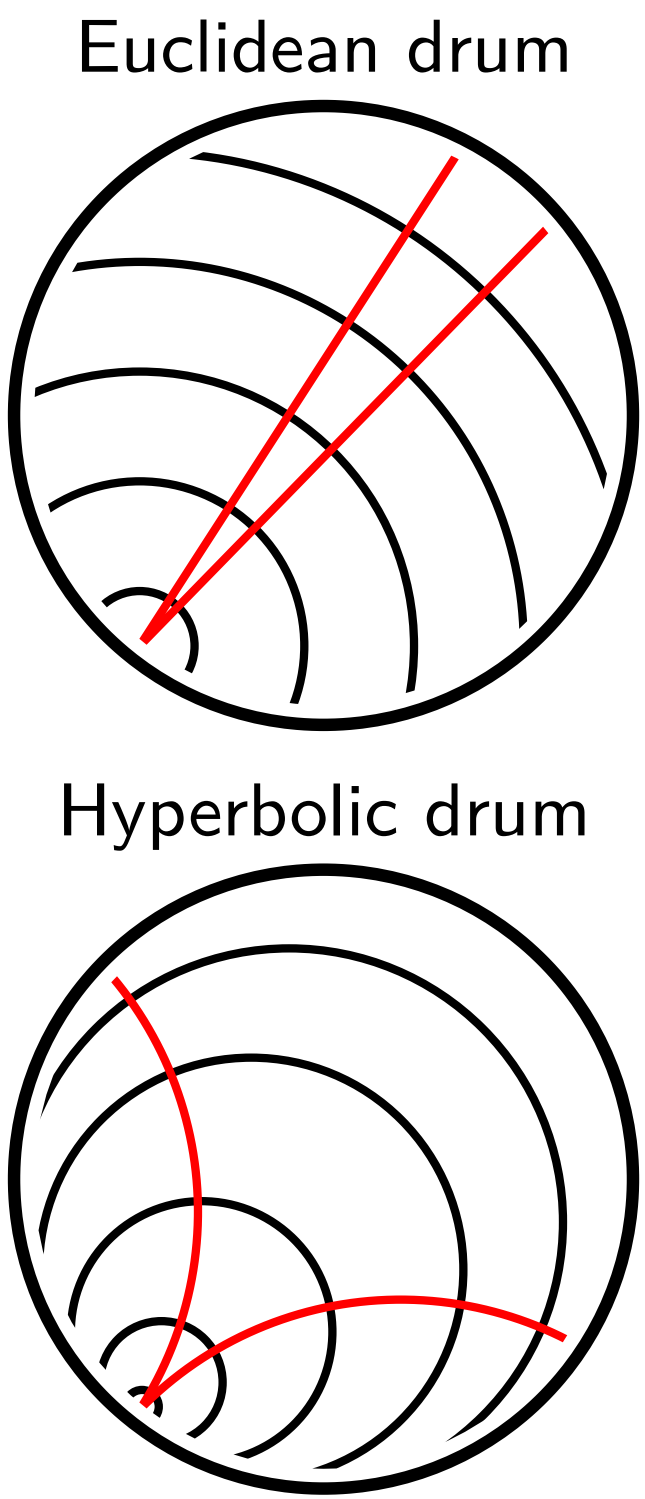
Measured eigenmodes

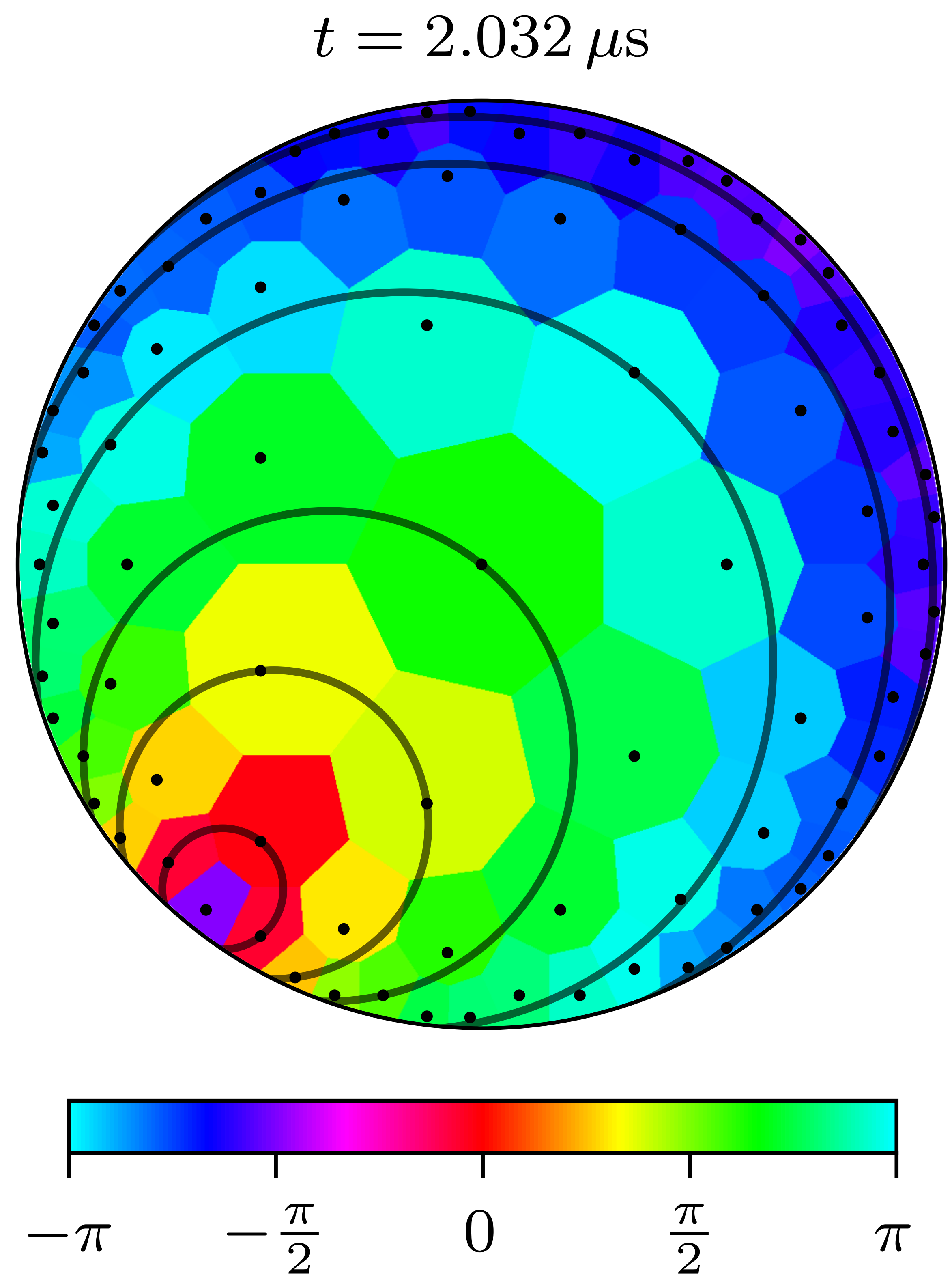






Signal propagation

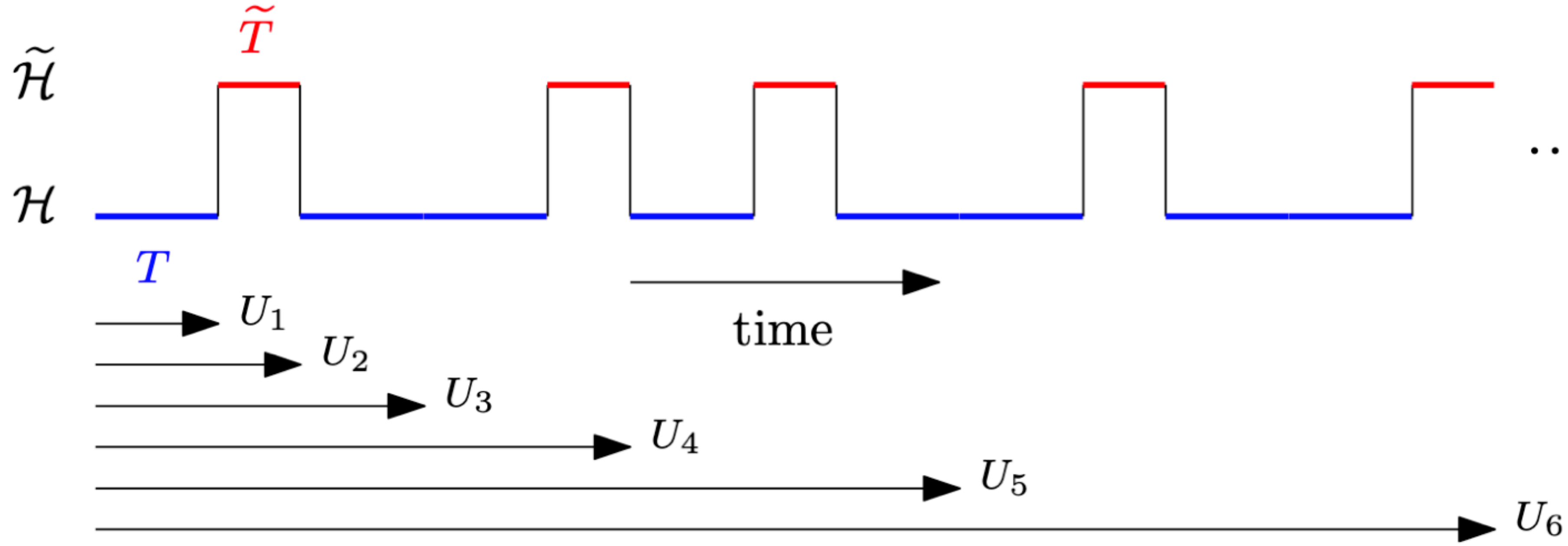




Take away

Electrical circuits are ideal platform for studying classical physics in hyperbolic space, test hyperbolic band theory, …

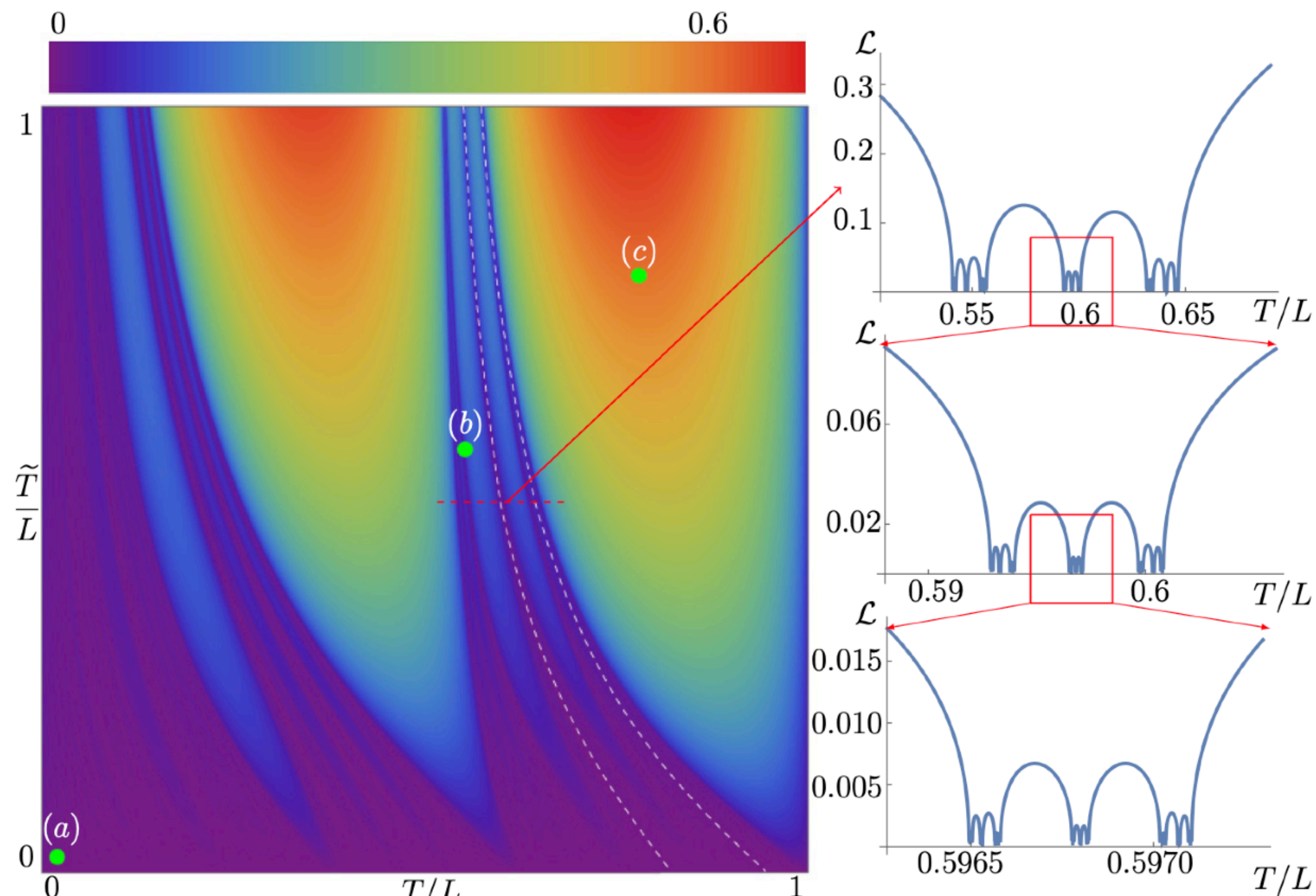
Quasiperiodic drive



Fibonacci sequence

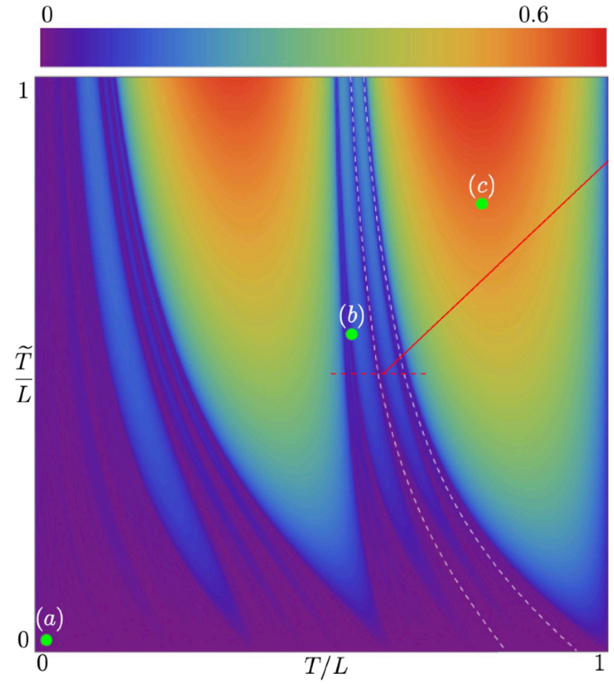
$$U_{n+2} = U_n U_{n+1}$$

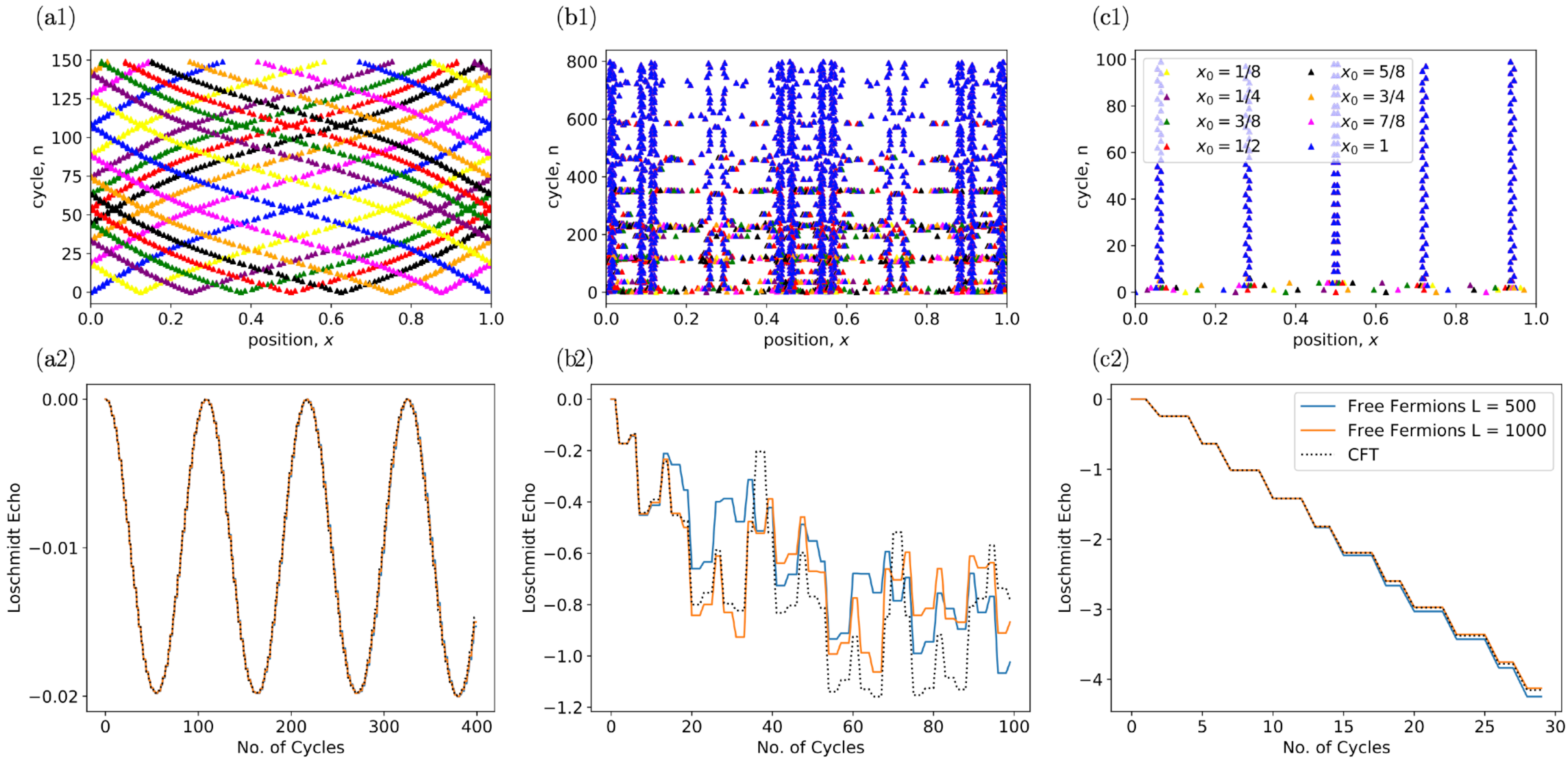
Fractal phase diagram with lines of exactly zero heating



Quasiperiodic drive

heating regimes: particles locate at only few fixed positions, independent of initial conditions





Outlook

Internal symmetries

Micromotion

Higher dimensions

Holographic perspective

Open systems

Phys. Rev. Research 2, 023085 (2020)

Phys. Rev. Research 2, 033461 (2020)

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It may be worth to study HOW systems heat up!

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