Quantum Information and the Black Hole Interior

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Mostly based on work with: Y. Zhao

Outline

1. Review: black holes and quantum information

2. Quantum circuit model of the interior

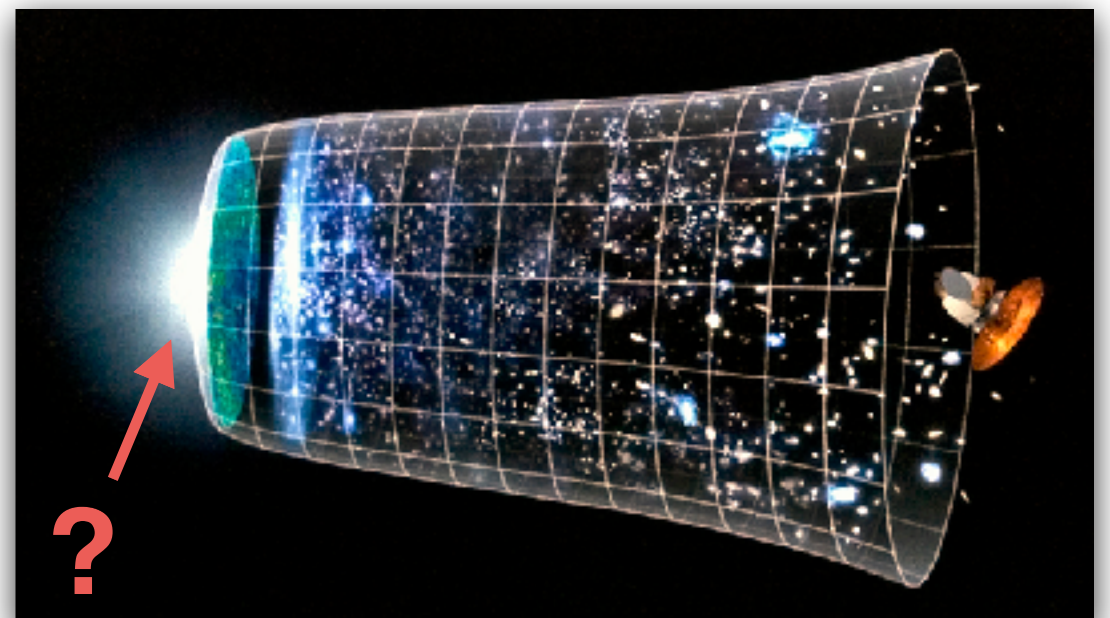
3. Collisions behind the horizon

4. Operator size

5. Conclusion

- Dynamics of spacetime geometry in extreme situations: quantum effects can be important or dominant

Cosmology



The beginning of the universe…?

Black holes

[Event Horizon Telescope '19]

Black hole interior?

Curvature singularity?

Thermodynamic properties?

The information problem

- Black holes look like thermodynamic systems with energy, entropy, temperature [Bekenstein '72] [Hawking '74]

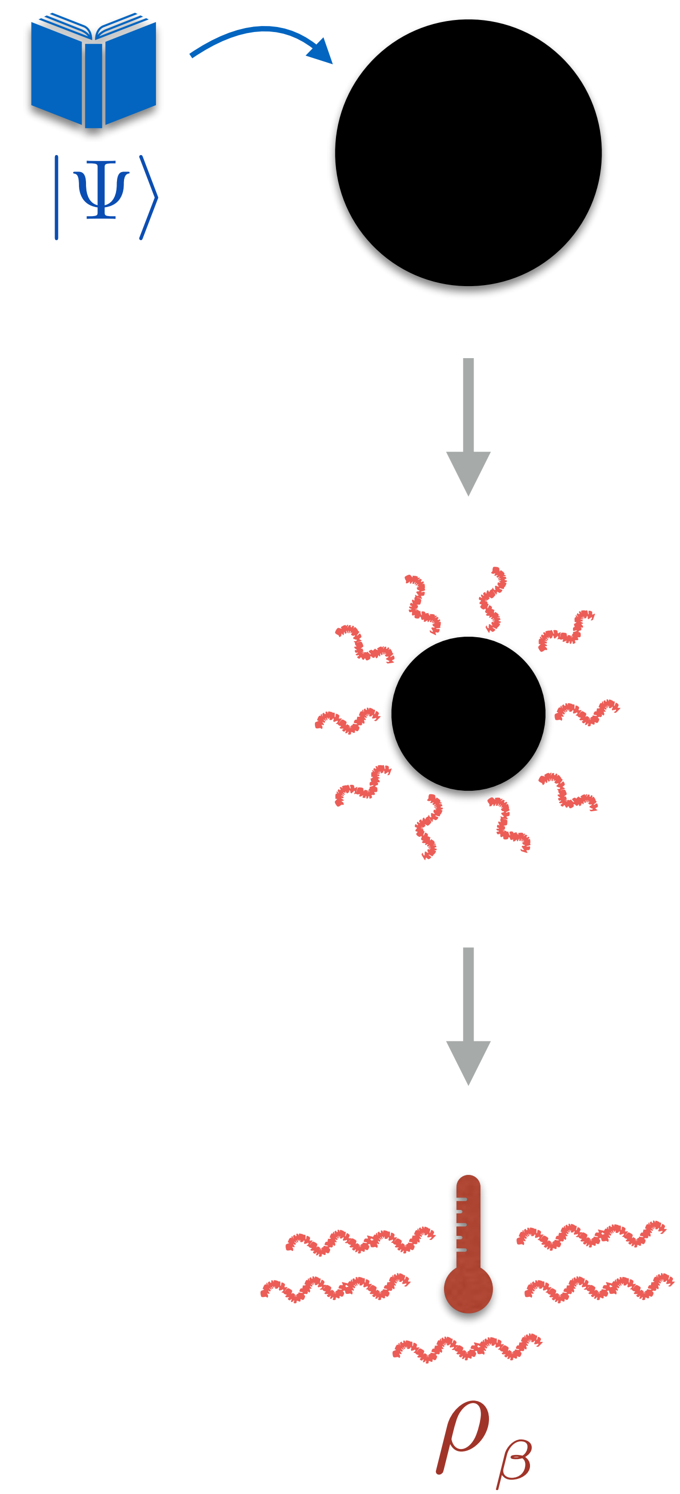
- Emit Hawking radiation and eventually evaporate

- Hawking radiation is thermal ("scrambled")
—> information seems to be destroyed

- Essence of the information paradox:

Tension between unitary quantum evolution and thermodynamic properties of the horizon (general relativity + Hawking radiation).

[Hawking '76] ... [Almheiri/Marolf/Polchinski/Sully '12] ...

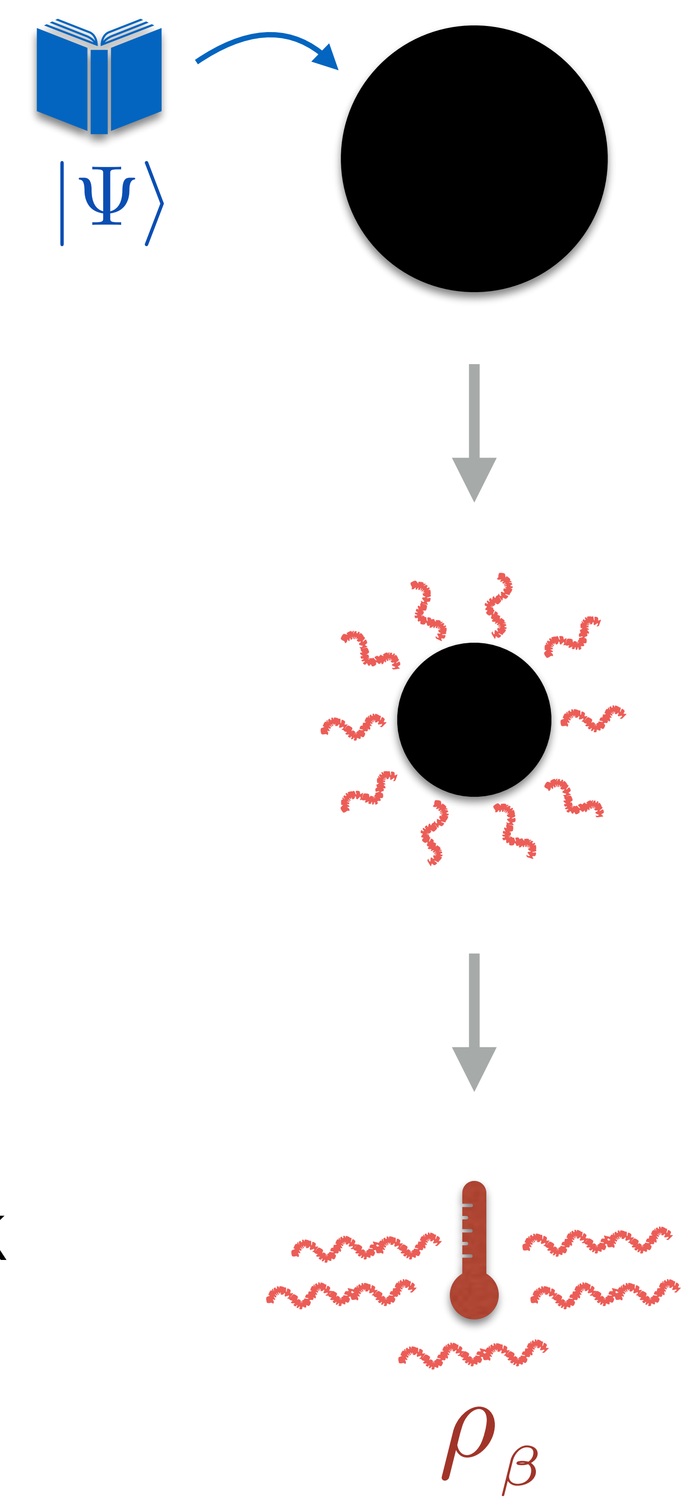


The information problem

Tension between unitary quantum evolution and thermodynamic properties of the horizon (general relativity + Hawking radiation).

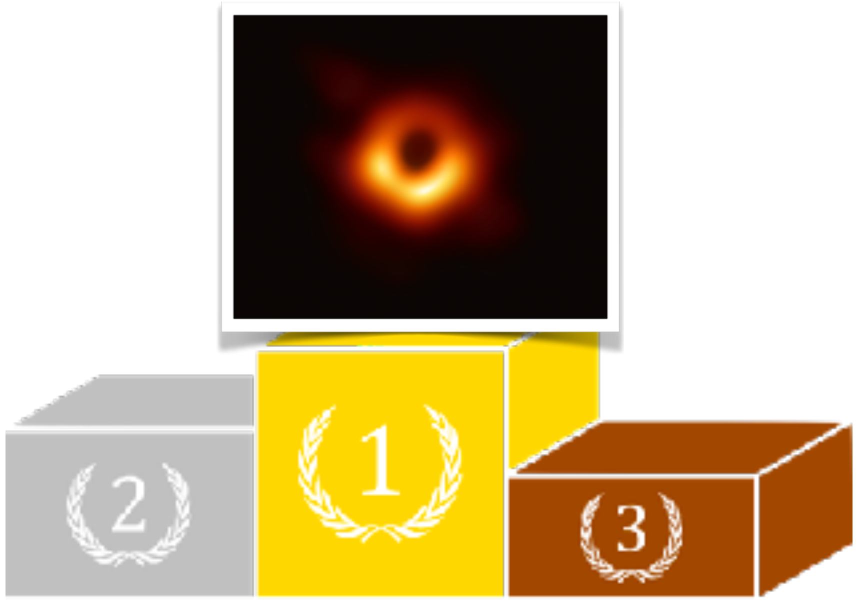
- Enormous progress…
  [Penington '19] [Almheiri/Engelhardt/Marolf/Maxfield '19]
- …and still many confusions

- Core theme: thermodynamic, statistical, and quantum information theoretic properties of black holes



Black Holes Excel at Information Theoretic Tasks

- The "densest hard drives":
  maximum entropy, given mass and size
  [Bekenstein '81]



- The "most ideal fluids":
  saturate shear viscosity bound
  [Kovtun/Son/Starinets '04]

- The "fastest information scramblers":
  take the shortest time to make information inaccessible to local measurements [Sekino/Susskind '08]

(…)

Holographic duality

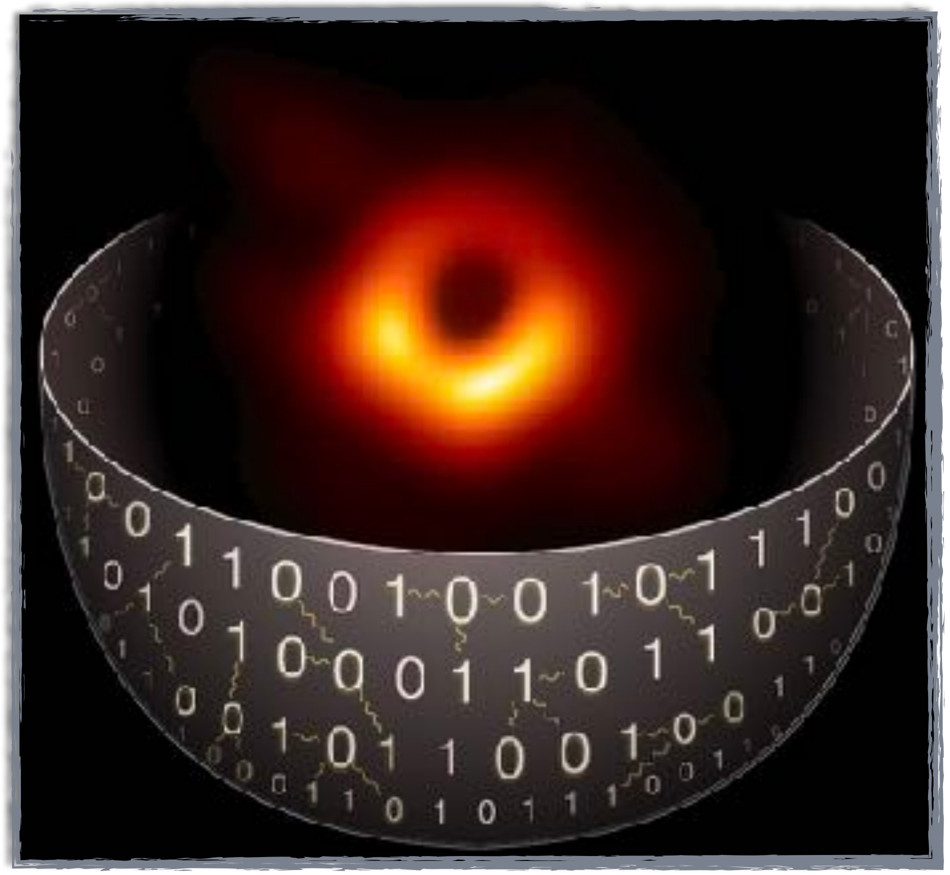
Quantum gravity in asymp. AdS_{d+1} ⟷ Conformal QFT_d

class. & qu. gravity — strongly coupled CFT

black holes — thermal states

grav. dynamics — entropy, hydrodynamics, chaos

geometry, locality, unitarity issues — entanglement, quantum information

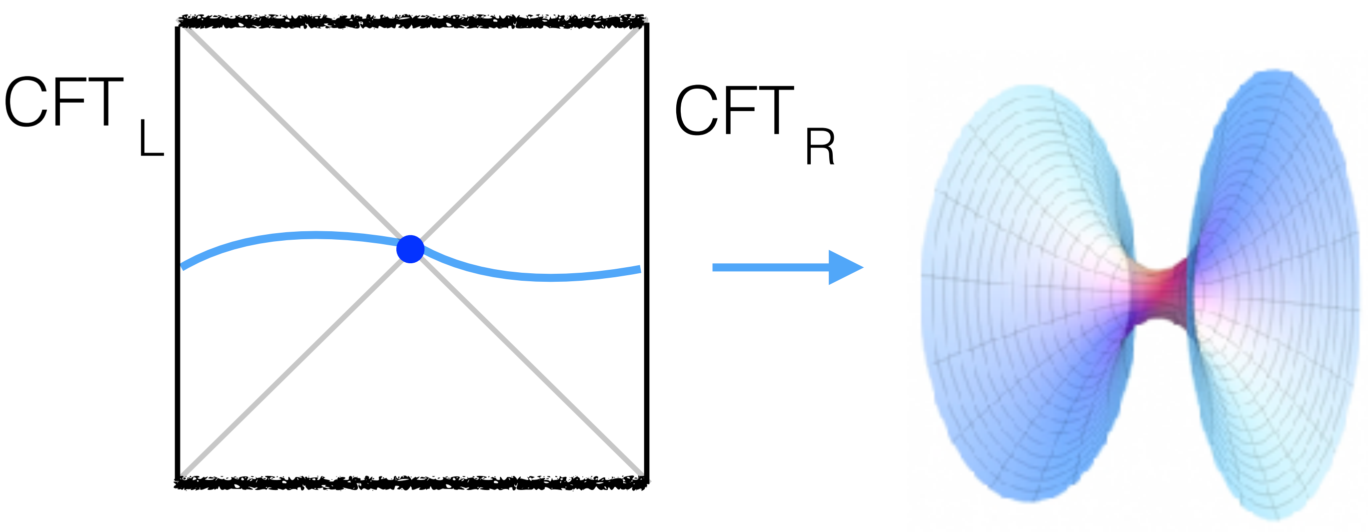


[Maldacena '97] [Gubser/Klebanov/Polyakov '98] [Witten '98]

Geometry and Entanglement

- Use AdS/CFT to learn about the fate of an infalling observer, black hole interior, and the singularity

- Setup: asymptotically AdS black hole



$$ds^2 = -\frac{4\ell^2\, du\, dv}{(1+uv)^2} + \ell^2 \left(\frac{1-uv}{1+uv}\right)^2 d\vec{x}^2$$

connected geometry

↕

$$|\mathrm{TFD}\rangle_{LR} = \sum_k e^{-\frac{\beta}{2} E_k}\, |E_k\rangle_L \otimes |E_k\rangle_R$$

highly entangled CFT state

$$\langle \mathrm{TFD}|\mathcal{O}_R|\mathrm{TFD}\rangle = \mathrm{tr}\left(\mathcal{O}_R\, e^{-\beta H_R}\right)$$

[Maldacena '01]

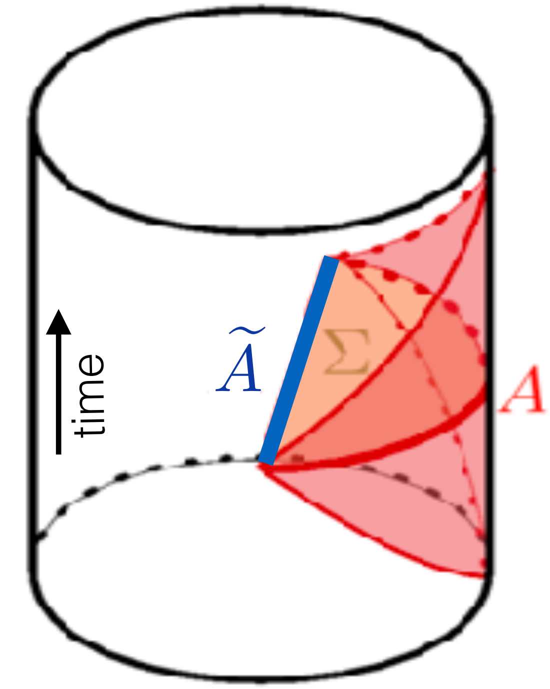
[Van Raamsdonk '10]

- **Entanglement** of the dual CFT state is believed to be crucial for having a connected geometry.

  - [Ryu/Takayanagi '06]: $S_{\mathrm{vN}}(\rho_A) = \dfrac{\mathrm{area}(\widetilde{A})}{4G_N}$

    [Hubeny/Rangamani/Takayanagi '07]

    $$\rho_A = \mathrm{Tr}_{A^c}(\rho)$$
    $$S_{\mathrm{vN}}(\rho) = -\mathrm{Tr}(\rho \ln \rho)$$



  - Perturbing ρ_A constrains $\mathrm{area}(\widetilde{A})$
    => can derive **local Einstein equations** from entanglement

    [Faulkner/Guica/Hartman/Myers/Van Raamsdonk '13]
    [Faulkner/**FH**/Hijano/Parrikar/Rabideau/Van Raamsdonk '17]

  - Quantum corrections: $S_{\mathrm{vN}}(\rho_A) = \dfrac{\mathrm{area}(\widetilde{A})}{4G_N} + \underbrace{\mathcal{O}(G_N^0) + \mathcal{O}(G_N) + \ldots}_{S_{\mathrm{bulk}}}$

    (crucial for info. paradox!)

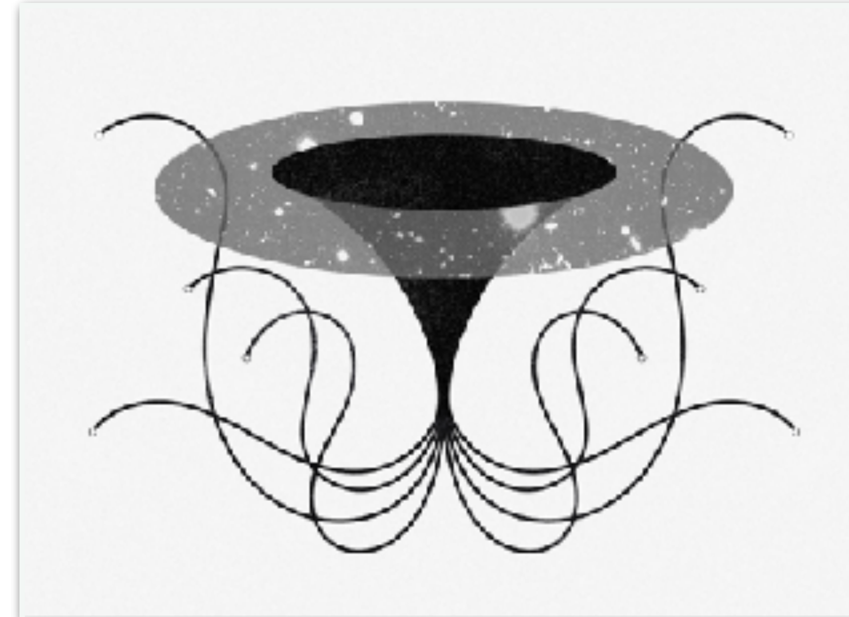
    [Faulkner/Lewkowycz/Maldacena '13]
    [Engelhardt/Wall '14]

  - [Maldacena/Susskind '13]: ER = EPR

    Einstein-Rosen bridge — entangled qubits

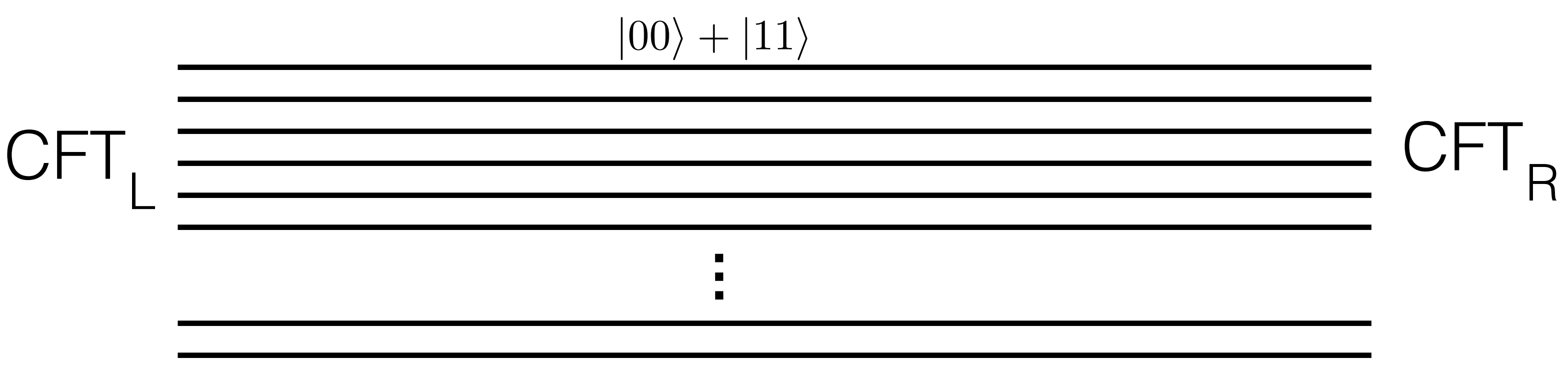
- ER = EPR ….. Can we test this??

$$|\mathrm{TFD}\rangle_{LR} = \sum_k e^{-\frac{\beta}{2}E_k} |E_k\rangle_L \otimes |E_k\rangle_R$$

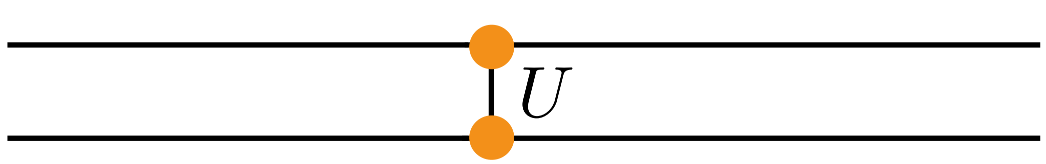


[Olena Shmahalo/Quanta Magazine]

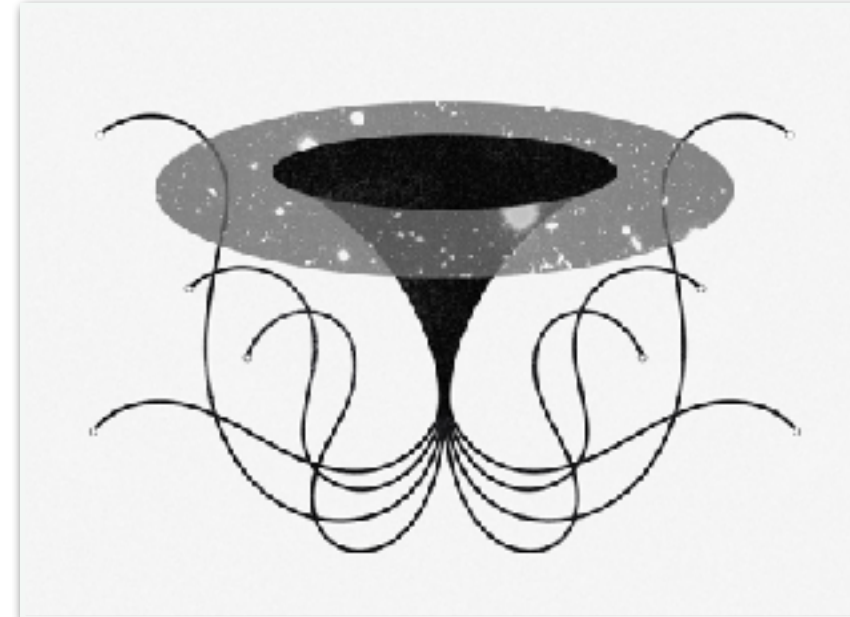
- Represent by EPR pairs (qubits):



- To model time evolution we perform operations on the qubits —> construct a **quantum circuit**
  - 2-qubit **quantum gates:**



- U can be **undone** by either side alone: act with U^{-1} on R or L



[Olena Shmahalo/Quanta Magazine]

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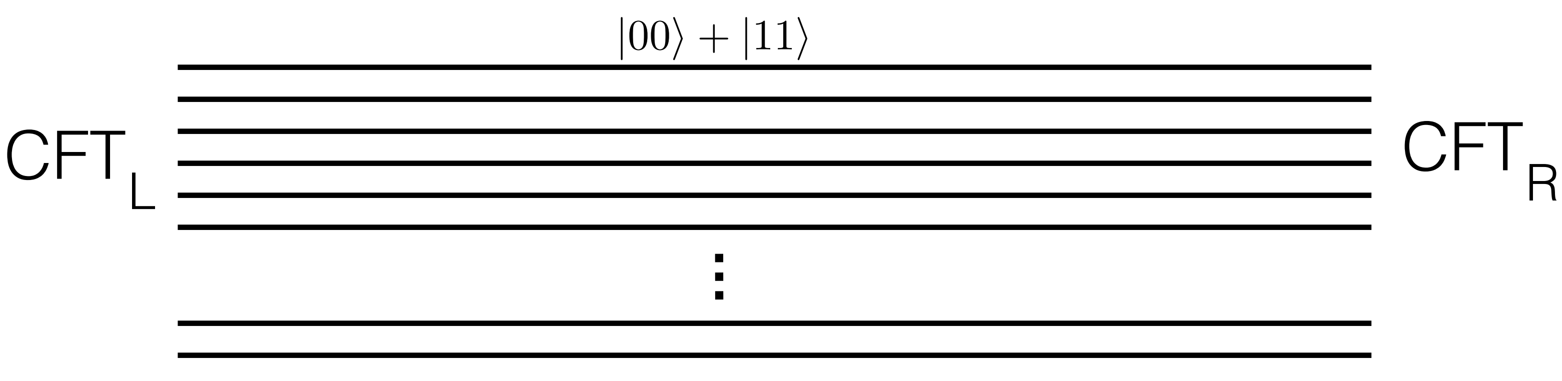

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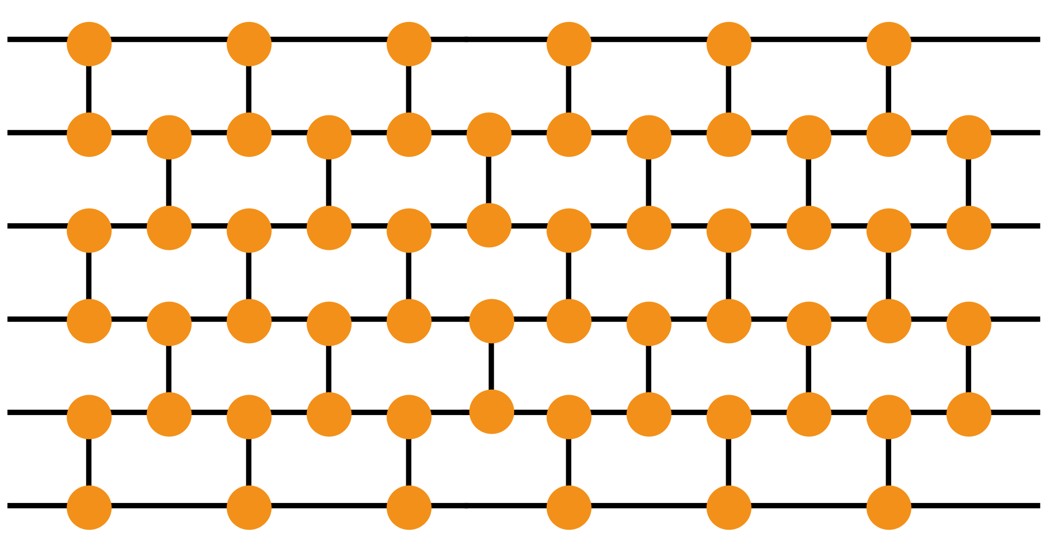
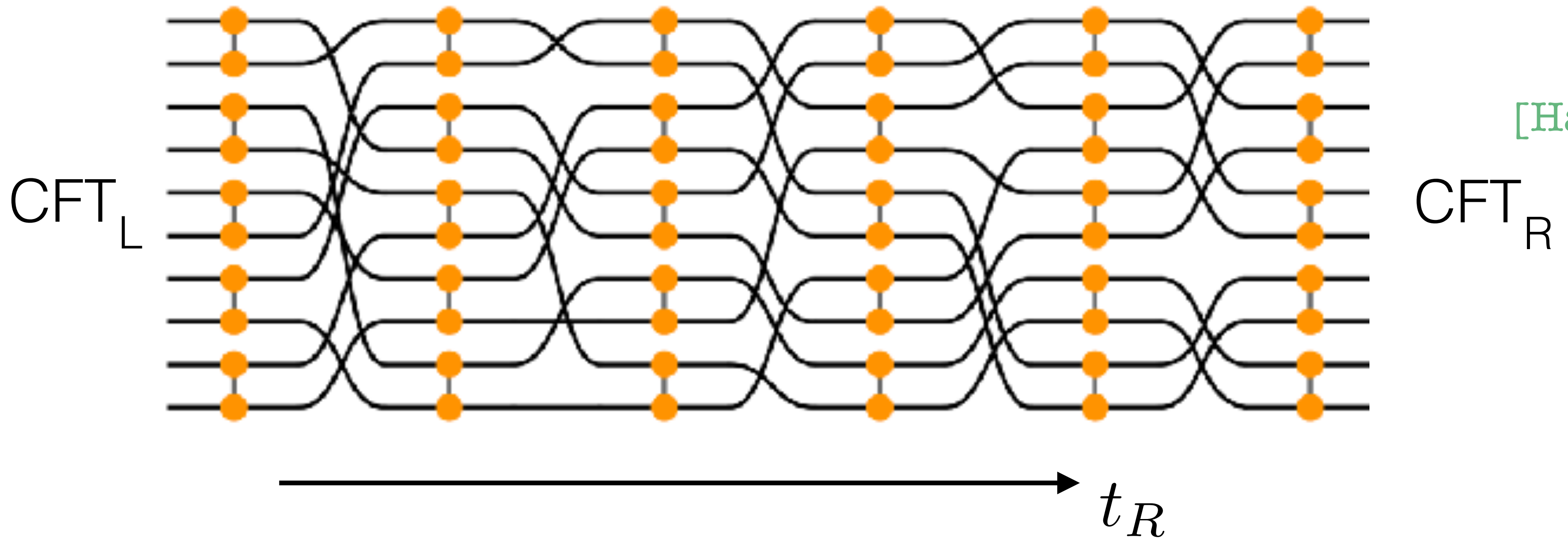
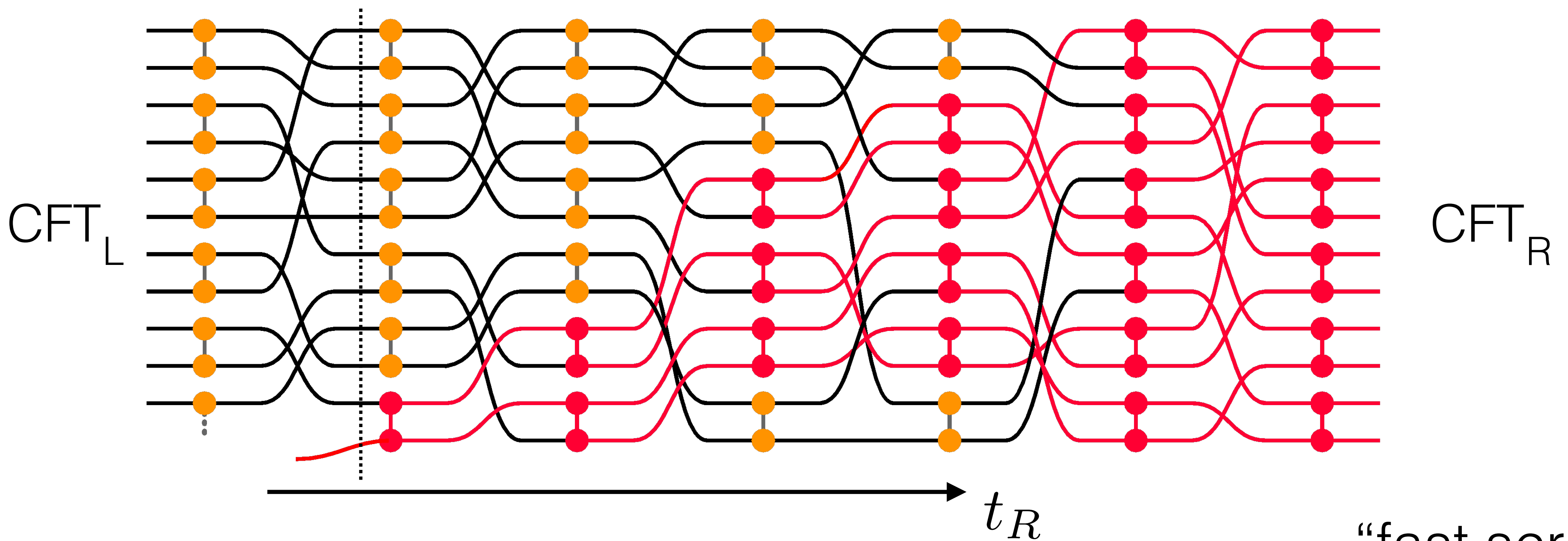


- Model for black hole time evolution: **random unitary all-to-all circuit**

[Hayden/Preskill '07]
[Swingle '12]
[Hartman/Maldacena '13]

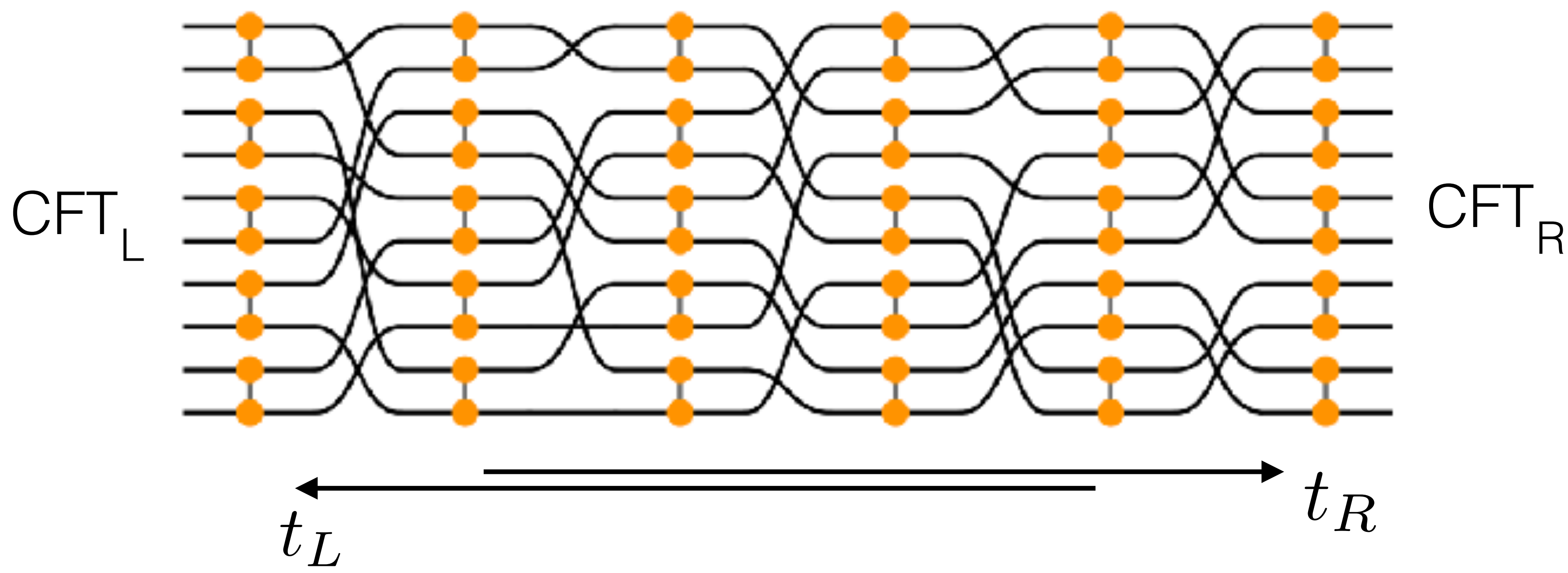


- Information spreads exponentially fast through the circuit:



"fast scrambling"

- Model for black hole time evolution: random unitary all-to-all circuit



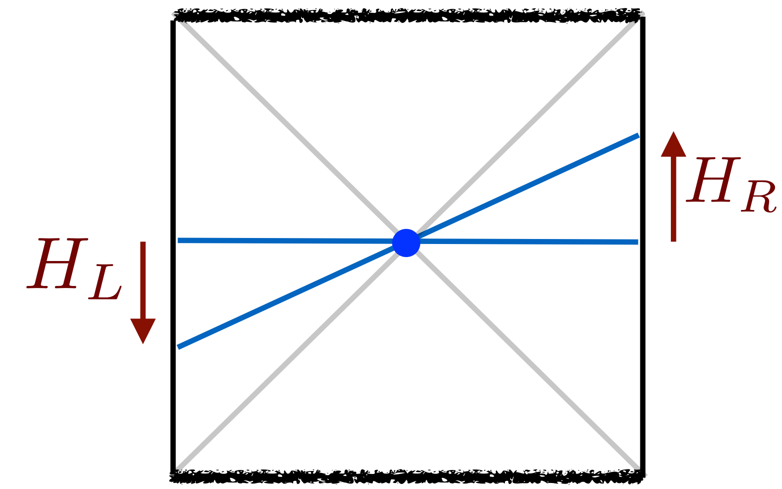
- Any gate could be implemented by either side
- Evolution in t_L can be **undone** by inverse evolution in t_R

- Depth of circuit is $t_R - t_L$
- Large depth means: the state of $\mathrm{CFT}_L \cup \mathrm{CFT}_R$ has a high computational complexity [Susskind '14]

- Note: the state of either CFT alone is always thermal
- Depth keeps increasing long after thermalisation

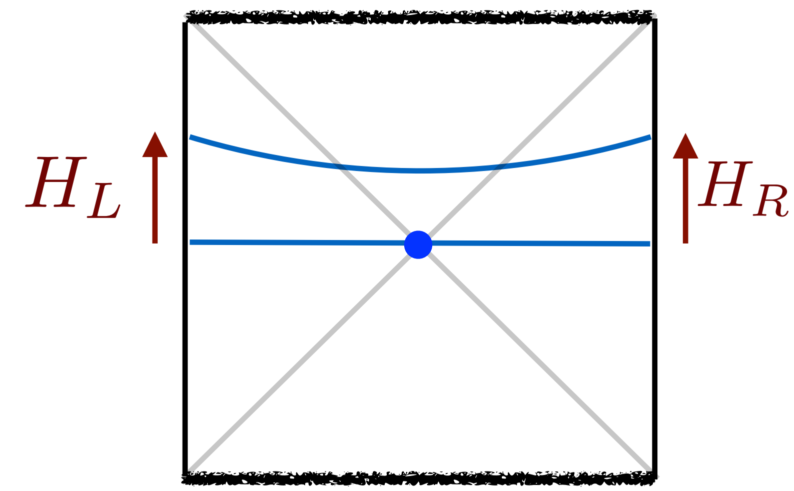
- Similar features in the TFD and black hole:

$$e^{it(H_R - H_L)}|\mathrm{TFD}\rangle_{LR} = |\mathrm{TFD}\rangle_{LR}$$



$$|\mathrm{TFD}(t)\rangle = e^{it\frac{H_R+H_L}{2}}|\mathrm{TFD}\rangle = \sum_k e^{-\left(\frac{\beta}{2}-it\right)E_k}|E_k\rangle_L \otimes |E_k\rangle_R$$

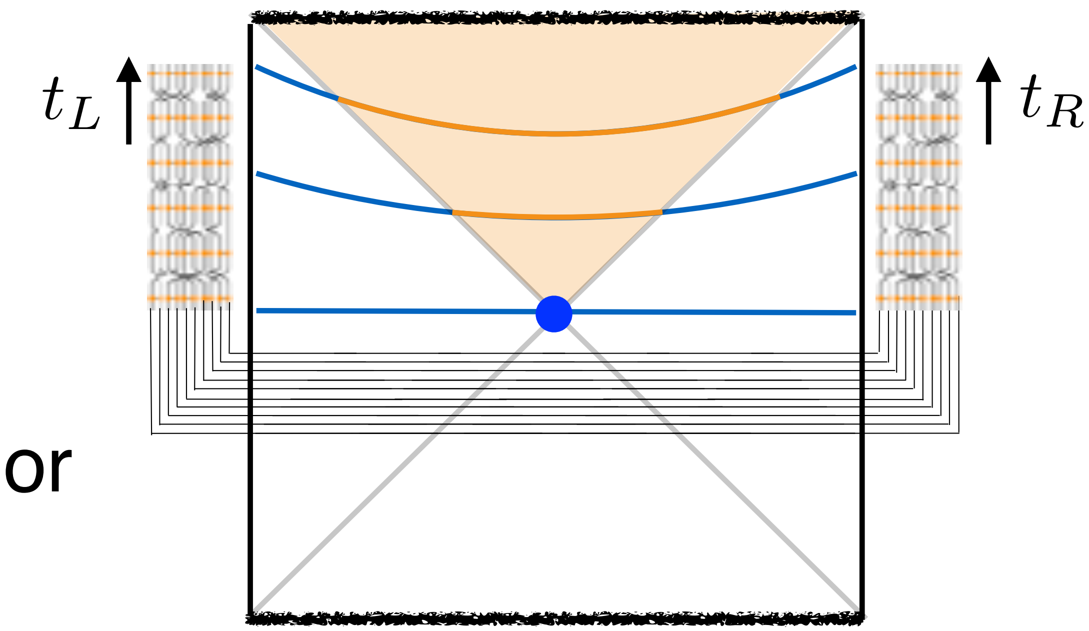
but still: $\mathrm{Tr}_L\left(|\mathrm{TFD}(t)\rangle\langle\mathrm{TFD}(t)|\right) = e^{-\beta H_R}$



- Evolving TFD with $H_L + H_R$ explores more of the interior
- This is invisible from the point of view of either CFT alone. Need $\mathrm{CFT}_L \cup \mathrm{CFT}_R$ to probe into the interior

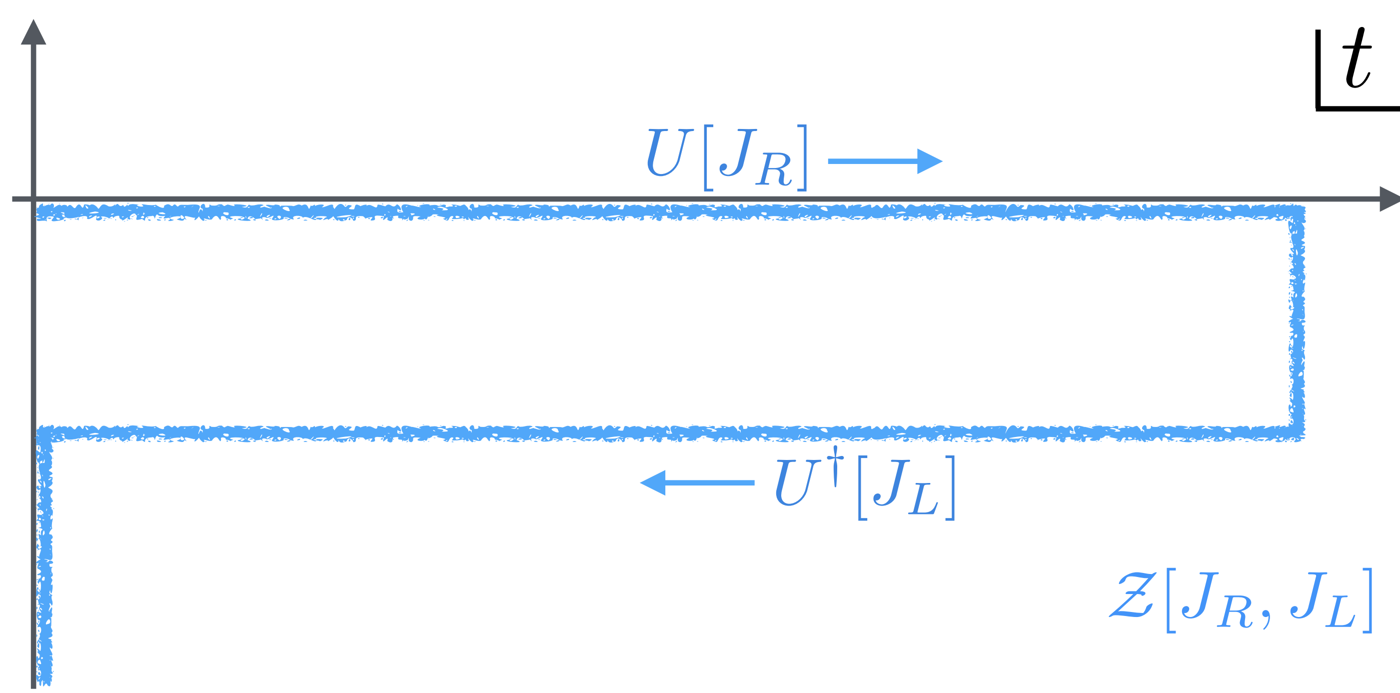
Circuit / black hole connection

- Proposal:
  (1) quantum circuit represents evolution of black hole interior
  (2) Depth of circuit (#gates) is proportional to spatial volume of interior



[Hayden/Preskill '07][Susskind '14]

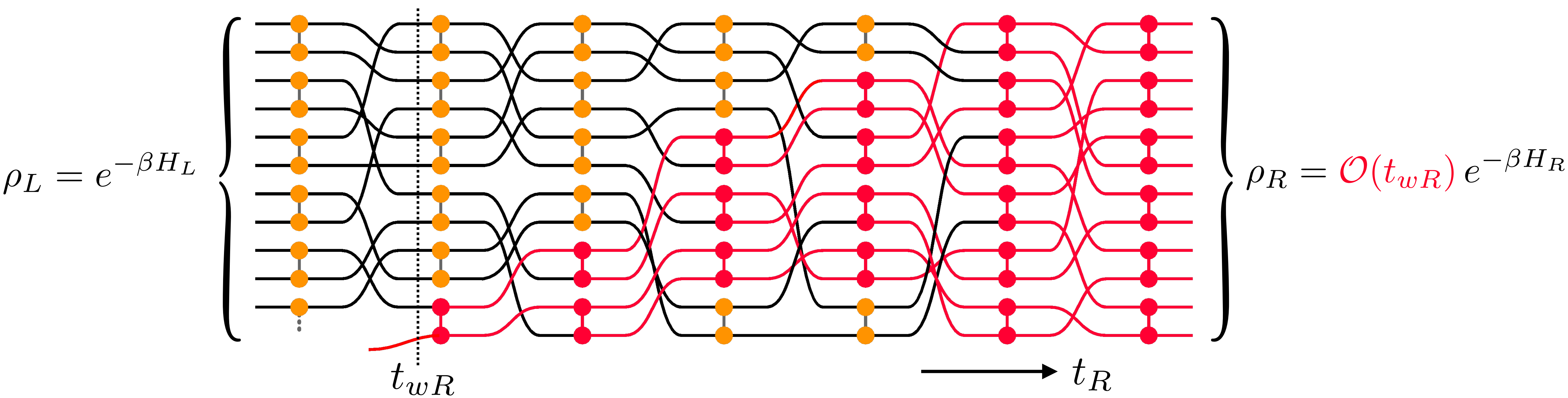
- N.b.: (1) is a 'quantum info' description of time evolution along the Schwinger-Keldysh contour:



$$\mathcal{Z}[J_R, J_L] = \mathrm{tr}\left(U[J_R]\,\rho_\beta^{\frac{1}{2}}\,U^\dagger[J_L]\,\rho_\beta^{\frac{1}{2}}\right)$$

Quantum butterfly effect

- Evolution in t_L can be **undone** by inverse evolution in t_R …
- …unless we change the state on one side (add a perturbation)!



- Epidemic model for "operator growth"

[Susskind/Zhao '14]
[Roberts/Stanford/Streicher '18]…

- Quantum butterfly effect:
  small perturbation has exponential effect on the future system

- R's p.o.v.:
  go back in time —> insert tiny perturbation —> evolve forward —> get very different state

Quantum butterfly effect

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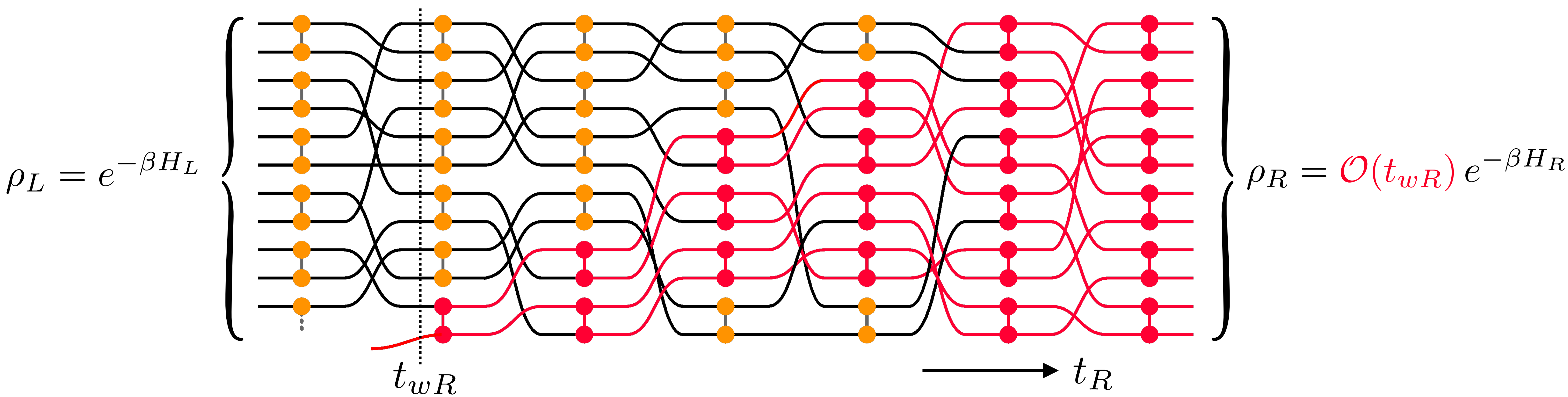


- Epidemic model for "operator growth"

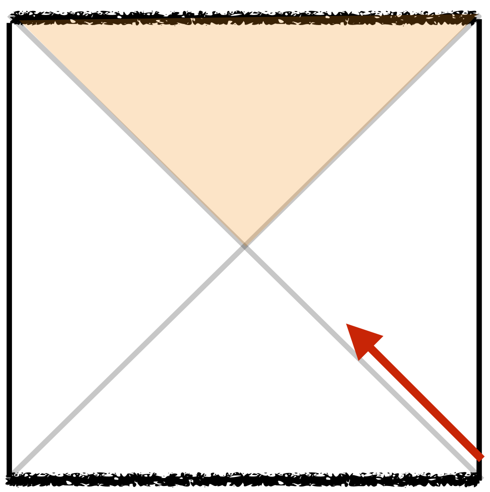
$$\frac{n_{\text{perturbed}}(t_R)}{n_{\text{tot}}} \sim \frac{1}{1+e^{-(t_R - t_{wR} - t_*)}} \approx \Theta(t_R - t_{wR} - t_*)$$

$$t_* = \frac{\beta}{2\pi} \log\left(\frac{S}{\delta S}\right)$$

"scrambling time"

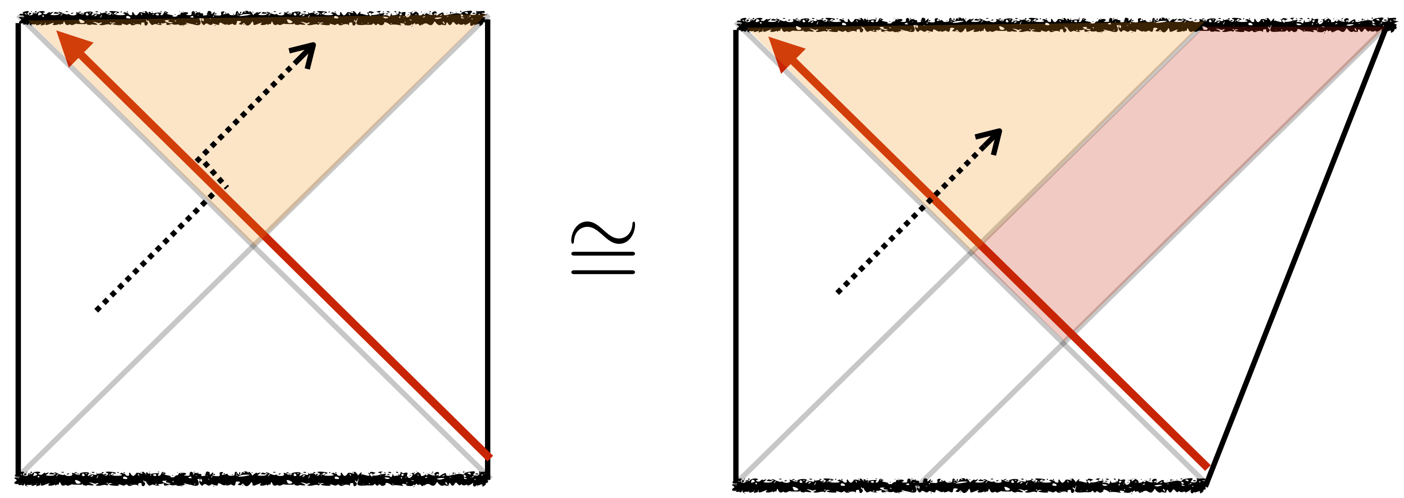
Shockwave geometry

- In gravity: send a signal from one side into the black hole



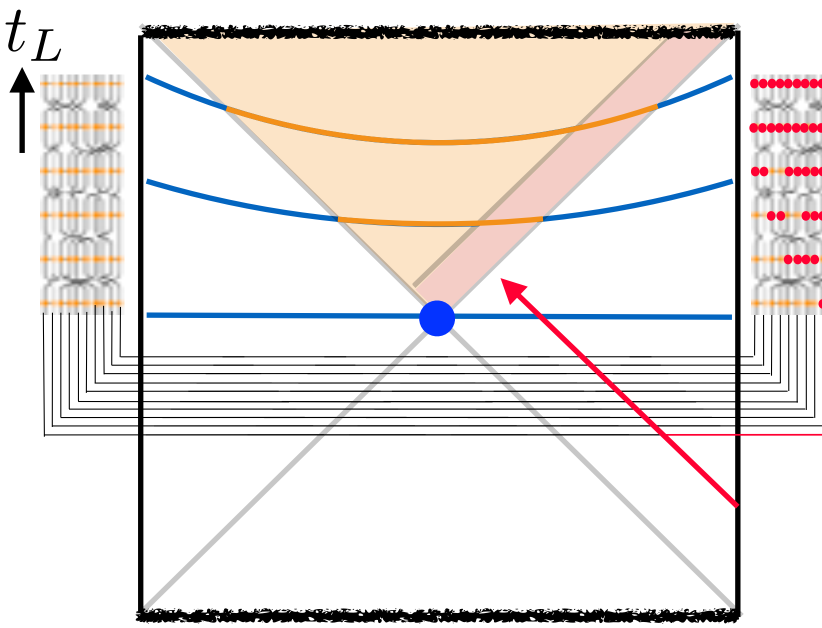
$|\Psi\rangle = \mathcal{O}_R(t_{wR})|\mathrm{TFD}\rangle$

Result is a shockwave geometry:



[Dray/'t Hooft '85]...[Shenker/Stanford '13]
[Stanford/Susskind '14]

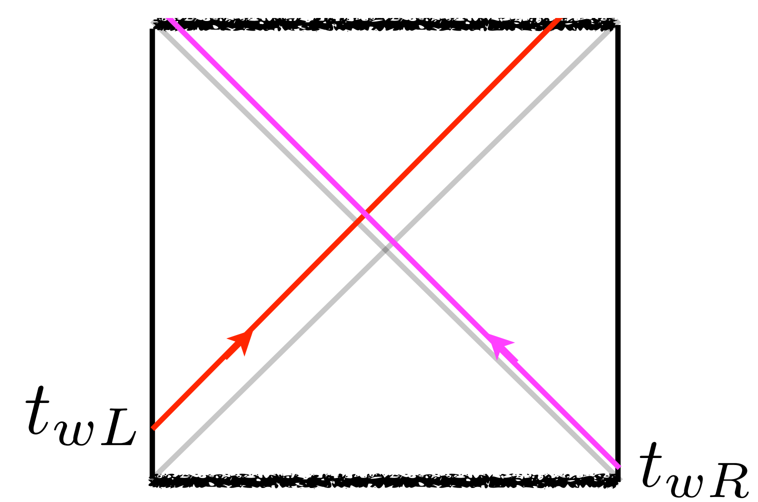
- <u>Proposal:</u>
  (3) Gates affected by perturbation represent the part of the interior geometry accessible by CFT_R only.



Collisions in the interior

Collision in the interior

- Puzzle: two signals sent into black hole can meet, even though the dual CFTs don't interact.



  - Send too late: no collision
  - Send earlier: collision in the interior
  - Send very early: highly boosted, expect strong backreaction

- Correspondingly, overlapping perturbations in circuit:

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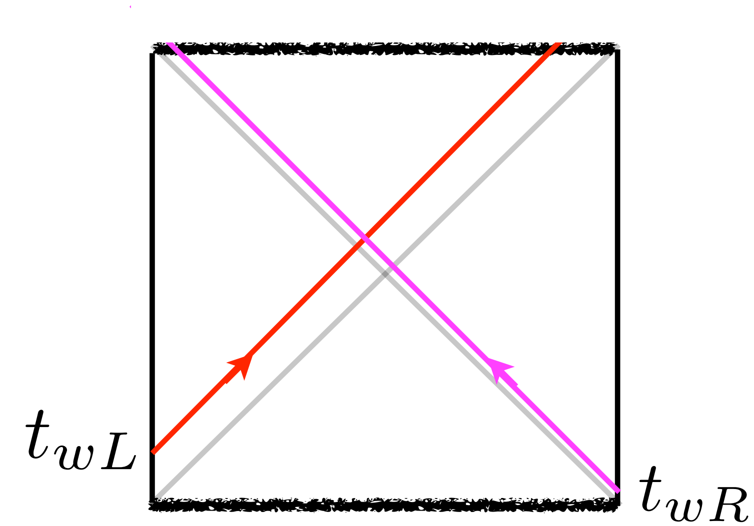

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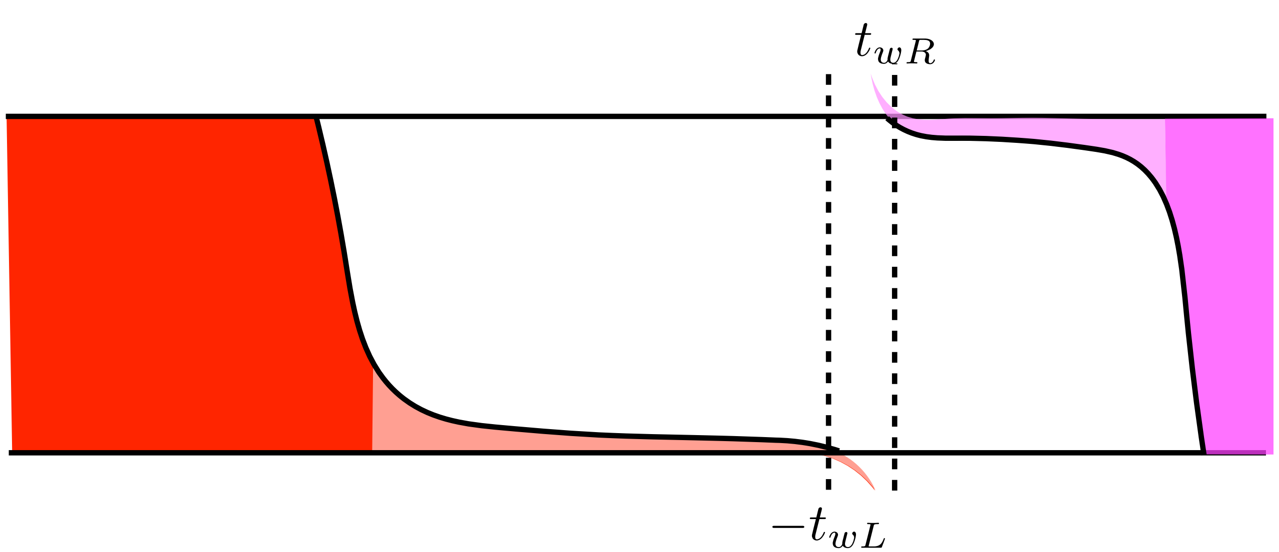

[Zhao '20]

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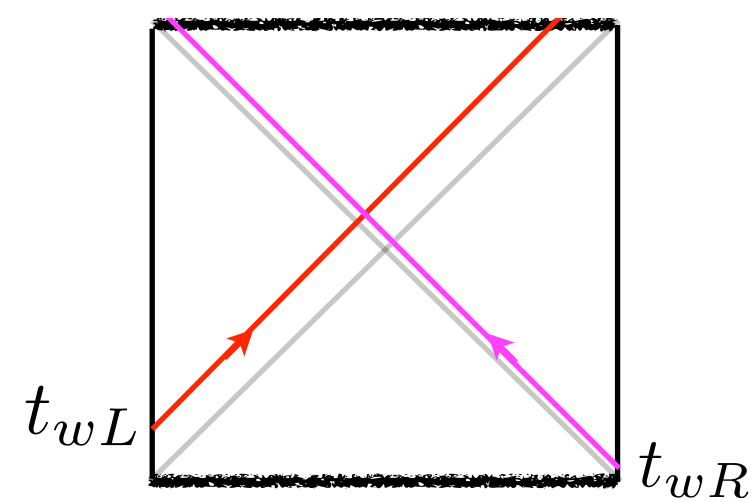

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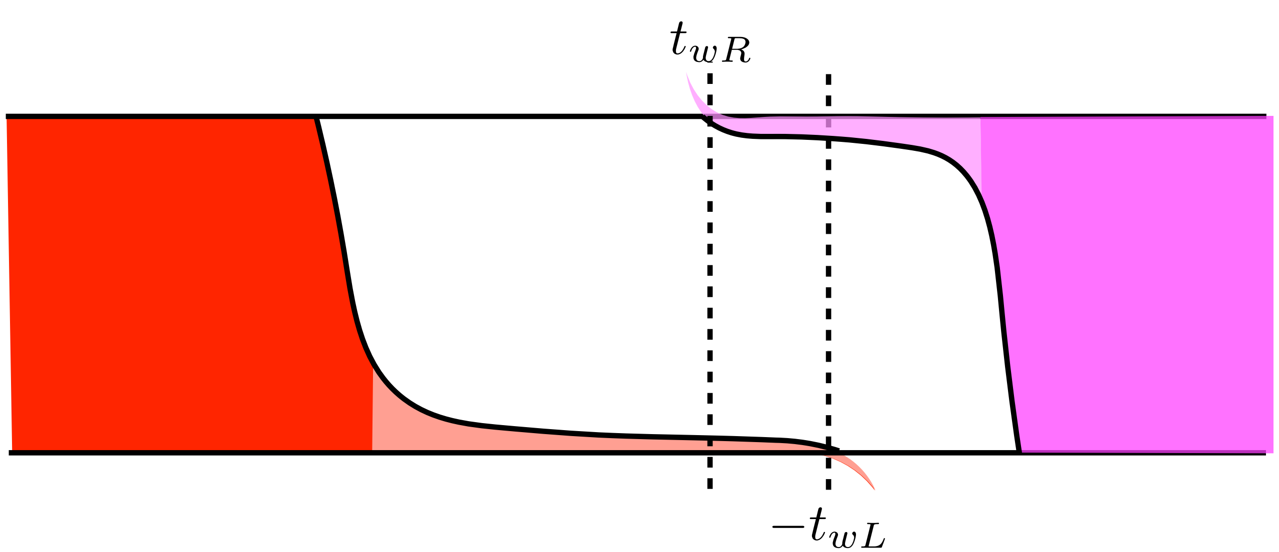

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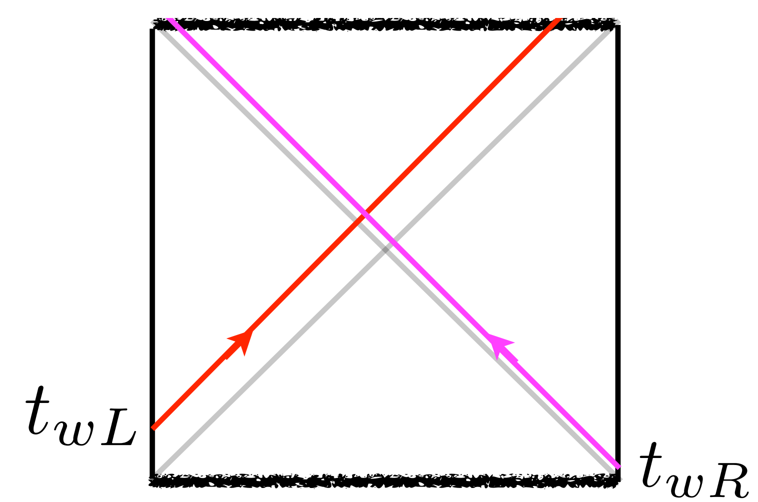

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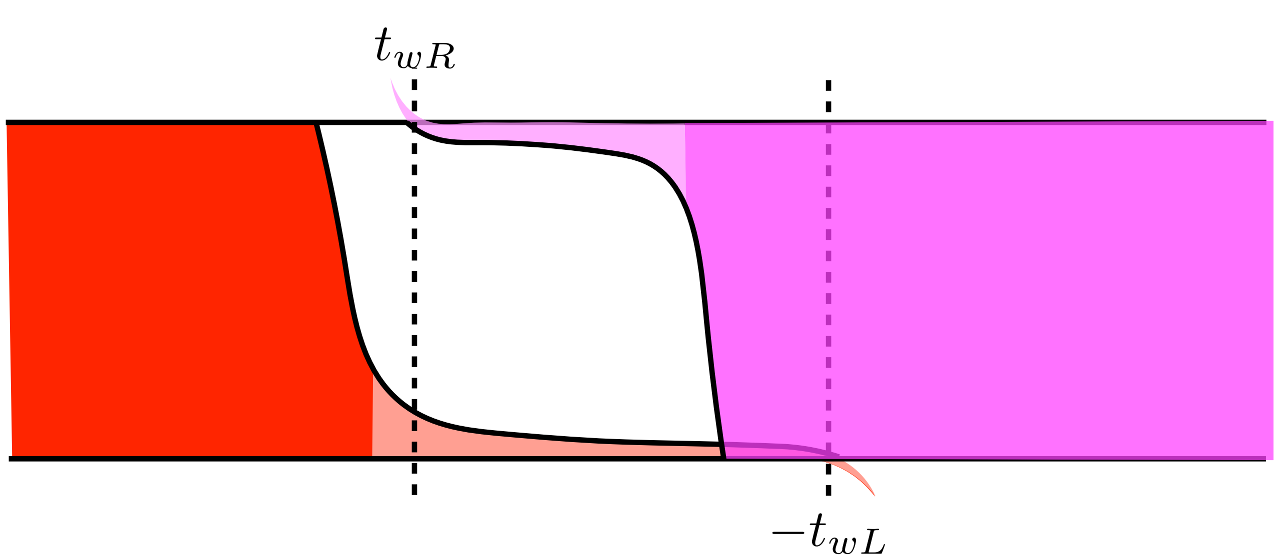

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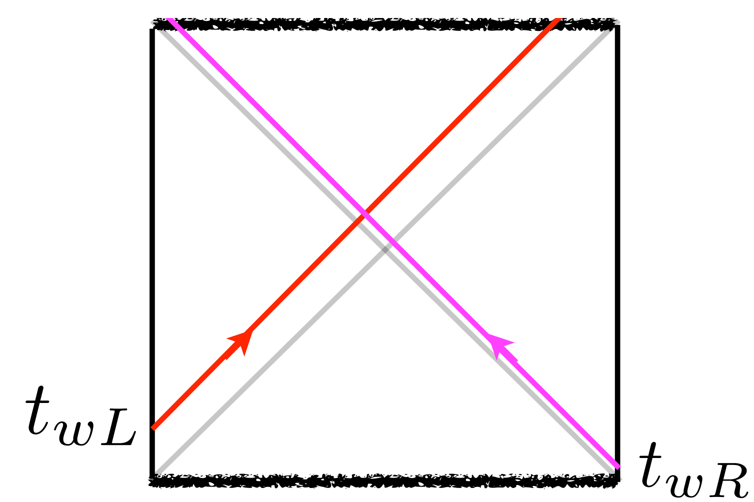

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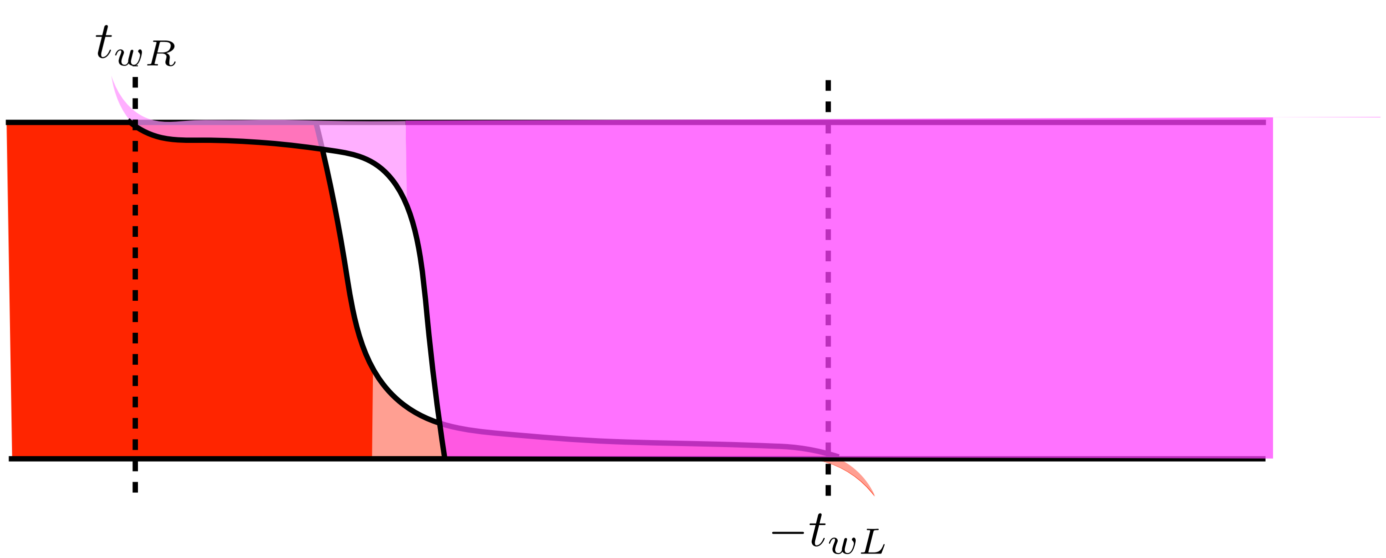

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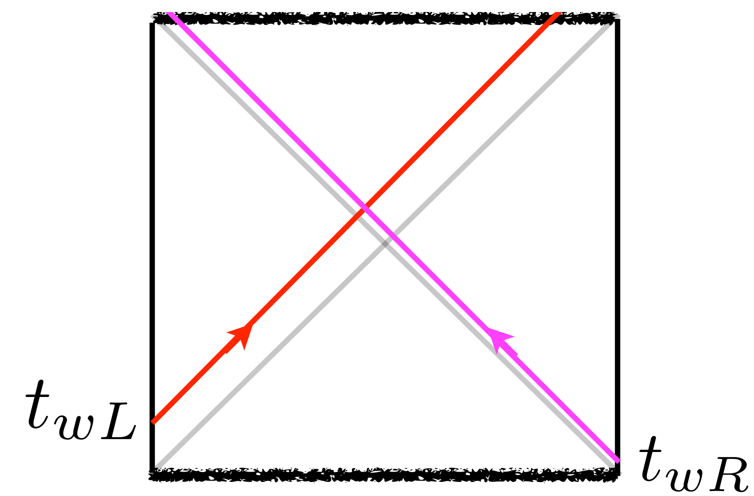

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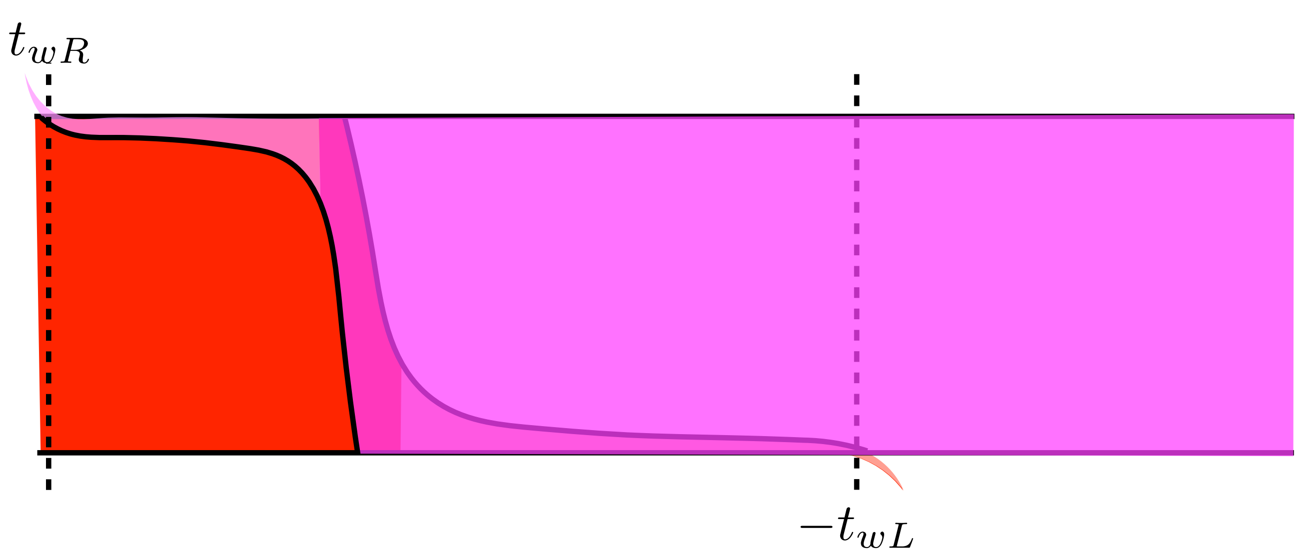
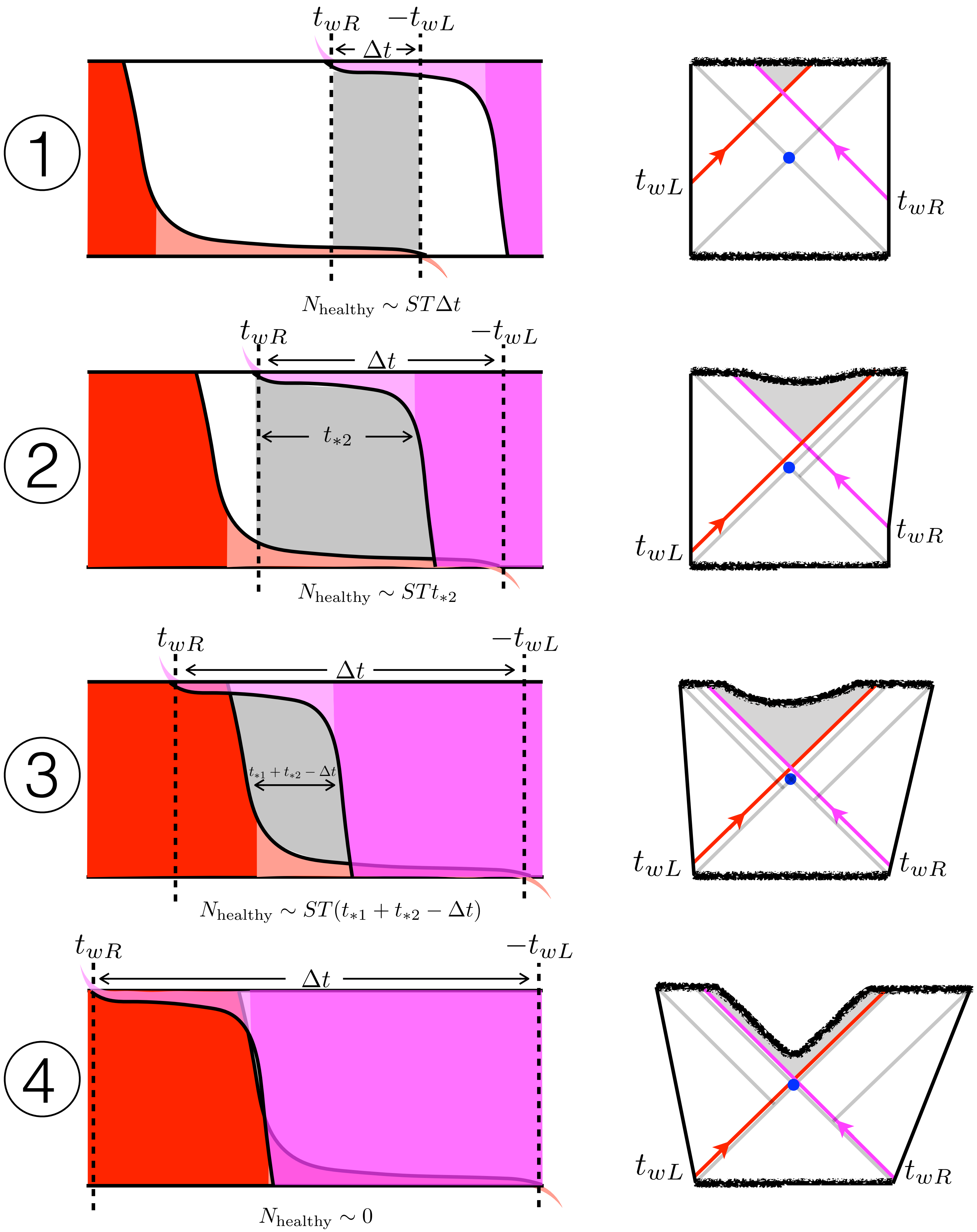
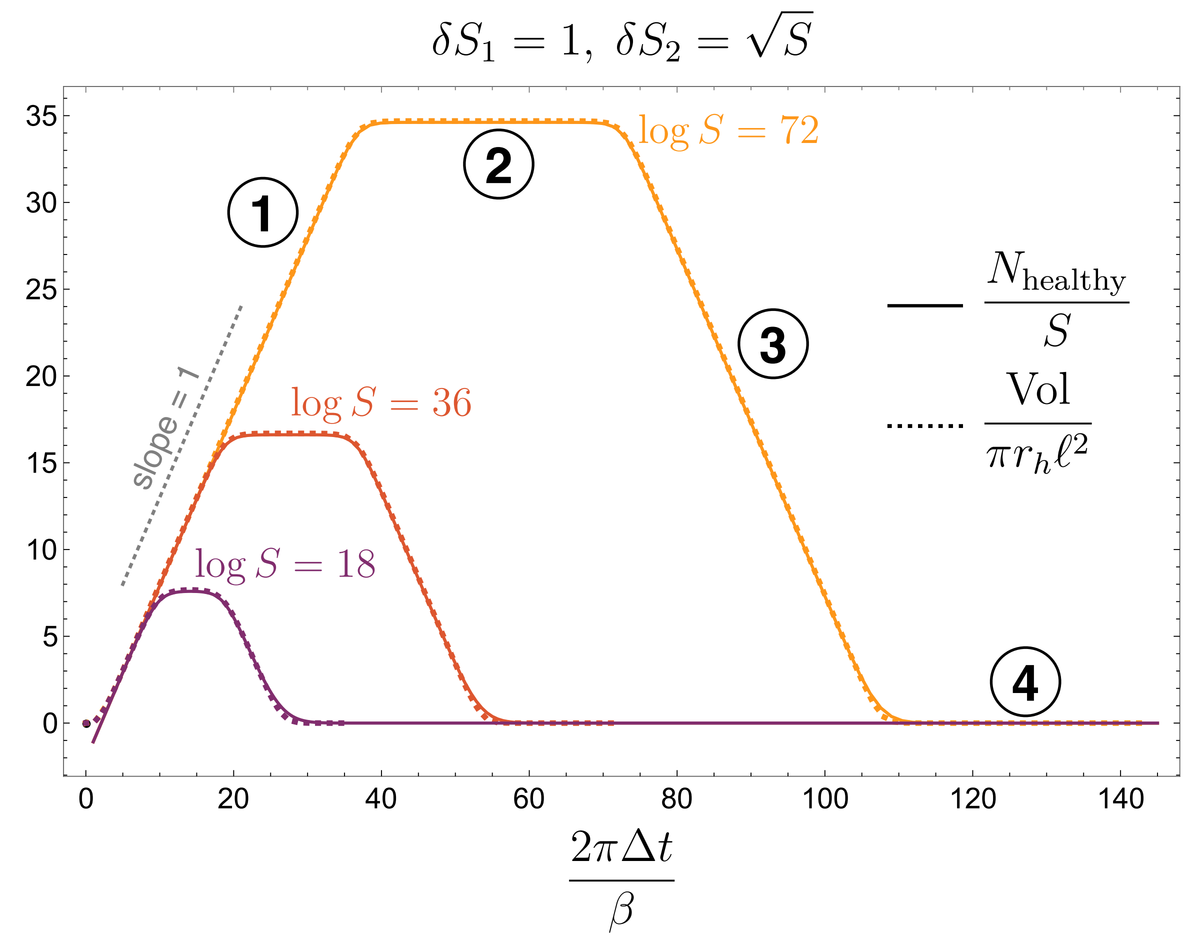


Proposal:
(4) Overlap in circuit describes gravitational interaction. It represents post-collision spacetime.

$\#(\text{healthy gates}) \propto \text{Vol}(\text{post-coll.})$

[Zhao '20]





- **Circuit model predicts:** post-collision volume becomes exponentially small after high-energy collision

[**FH**/Zhao '22]

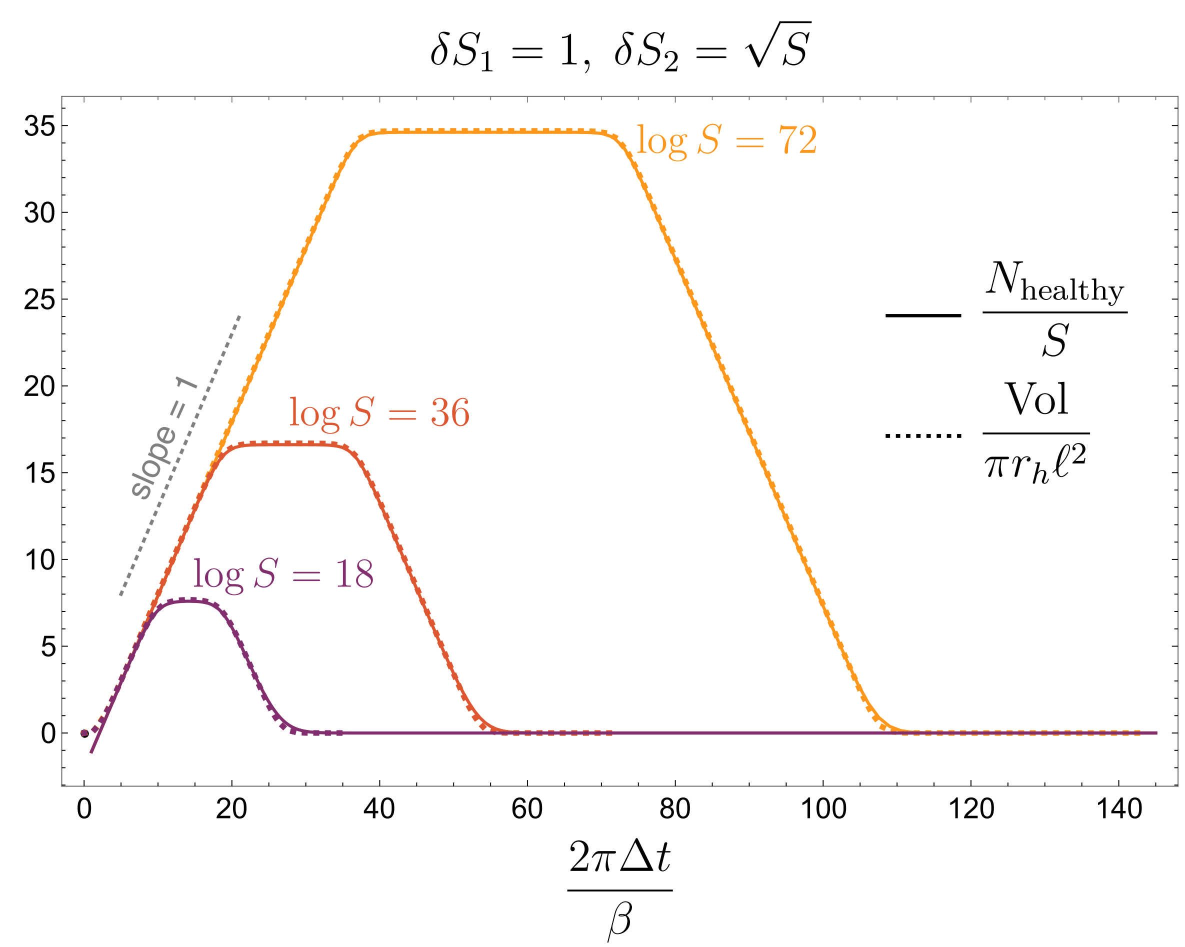
Checks

- Simplest check: spherically symmetric shocks in BTZ

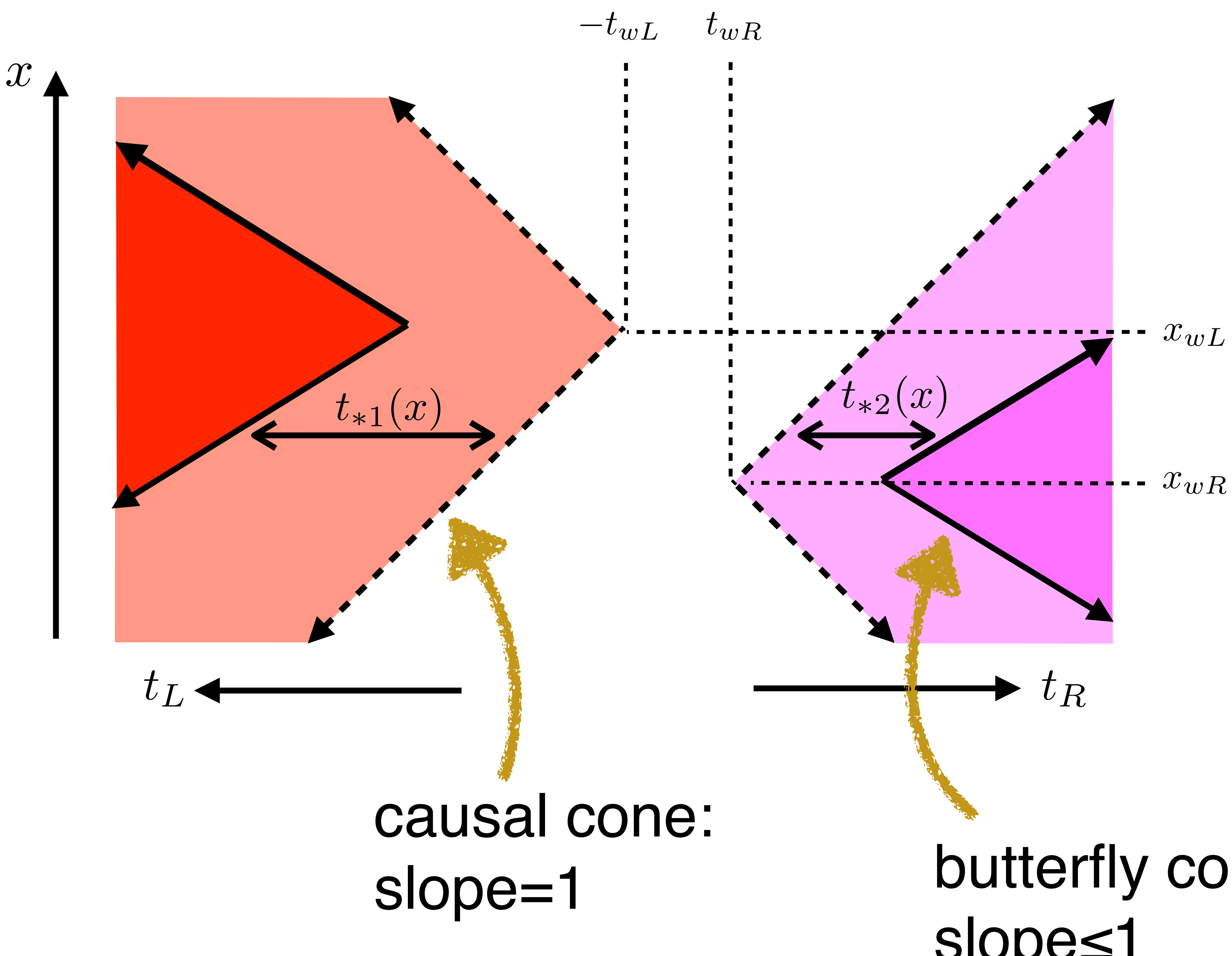
$$ds^2 = -\frac{4\ell^2}{(1+uv)^2}\,dudv + r_H^2\,\frac{(1-uv)^2}{(1+uv)^2}\,d\phi^2$$

  - Post-collision geometry remains locally AdS3
  - Glue BTZ patches along shock [Dray/'t Hooft '85]...[Shenker/Stanford '13]

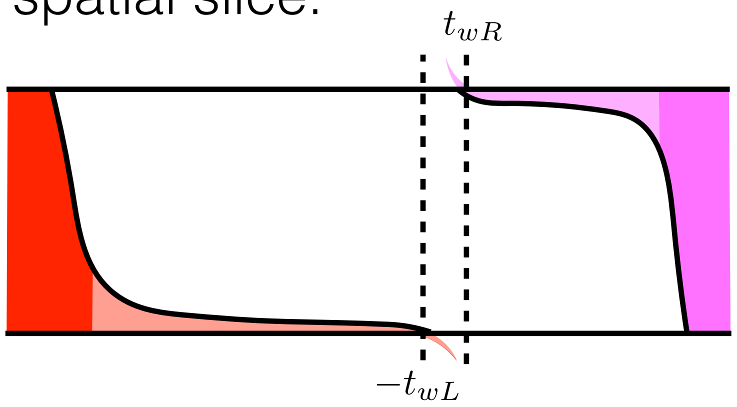
  - Very good match:



- More non-trivial checks: localized shocks (and higher dimensions)
- Add spatial direction(s) to the quantum circuit:



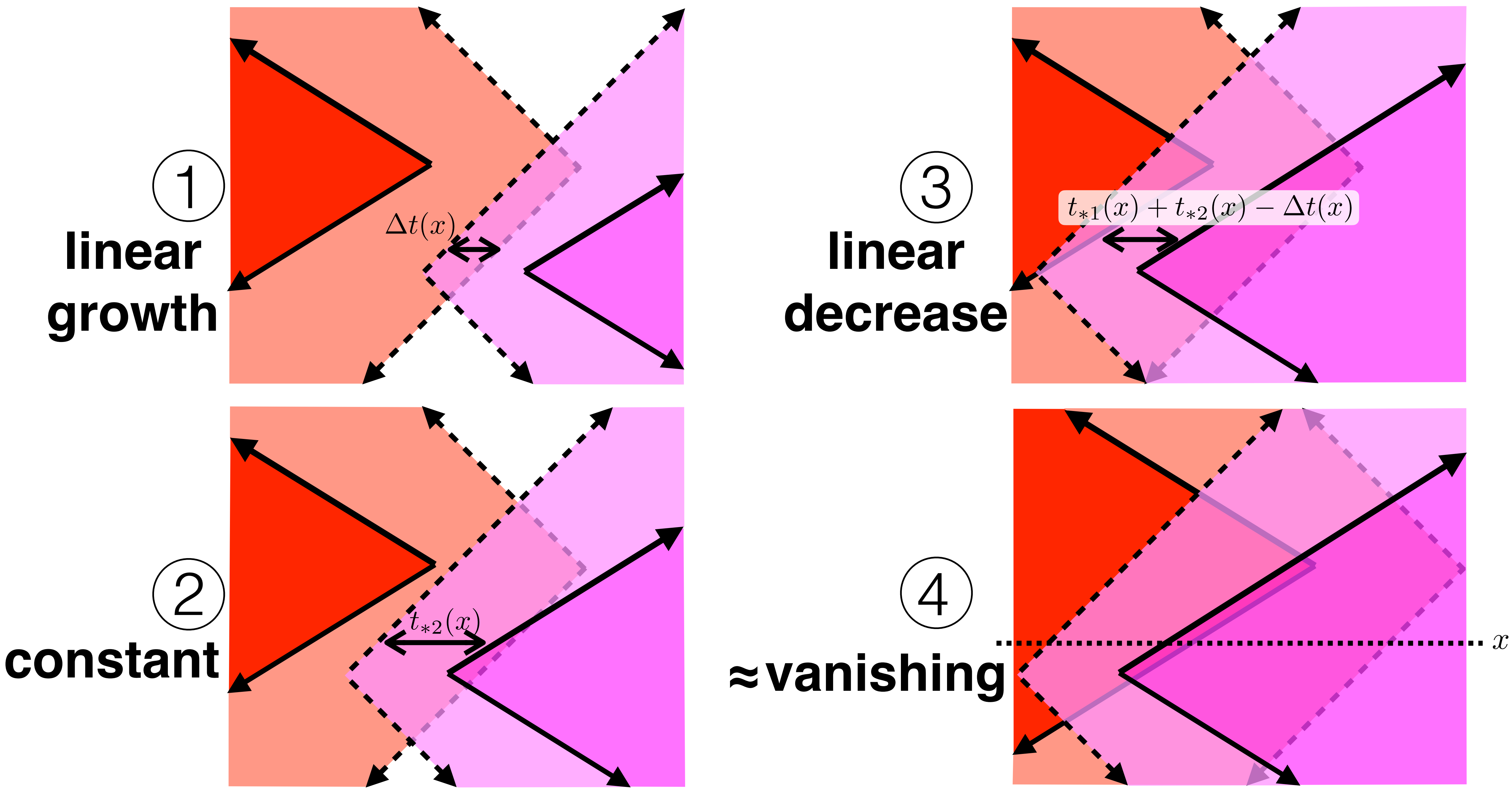
each spatial slice:



[Roberts/Stanford/Susskind '13]
[**FH**/Zhao '22]

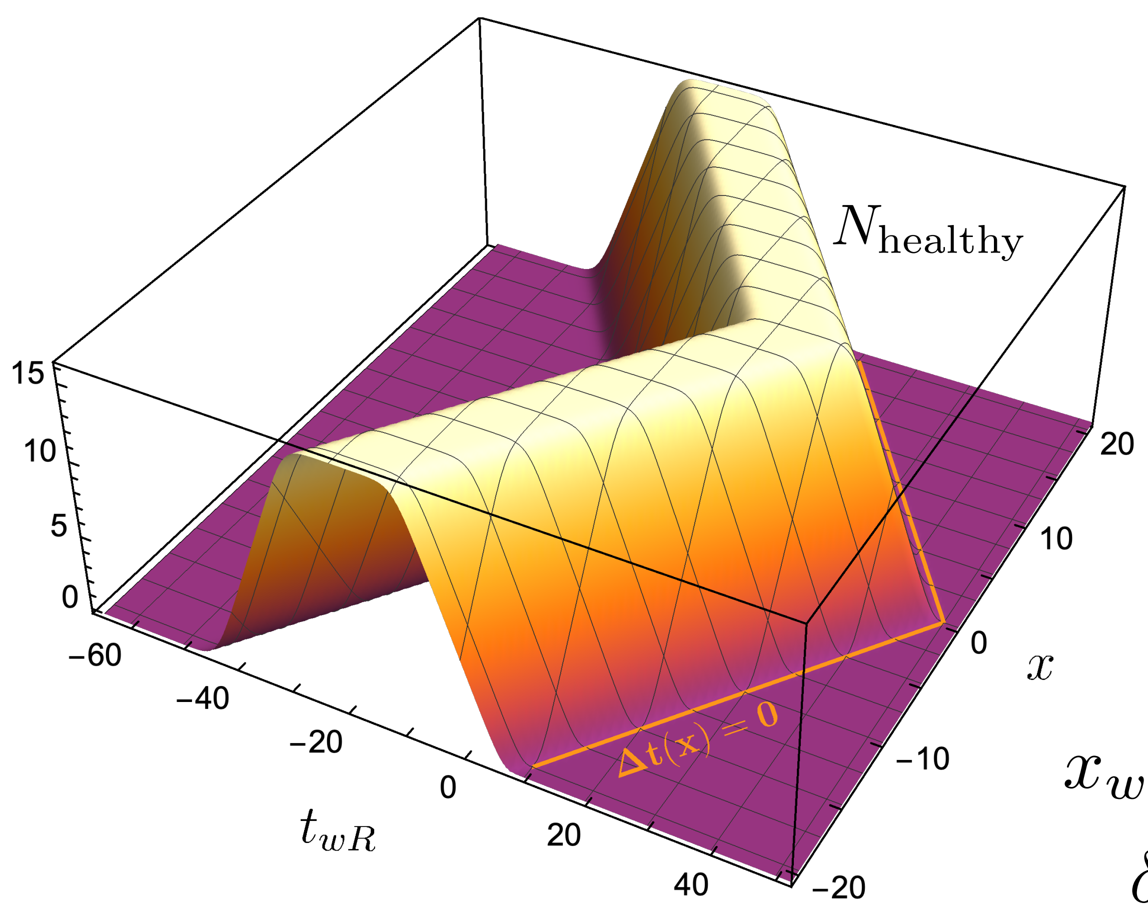
- Quantum chaos spreads ballistically with butterfly velocity v_B

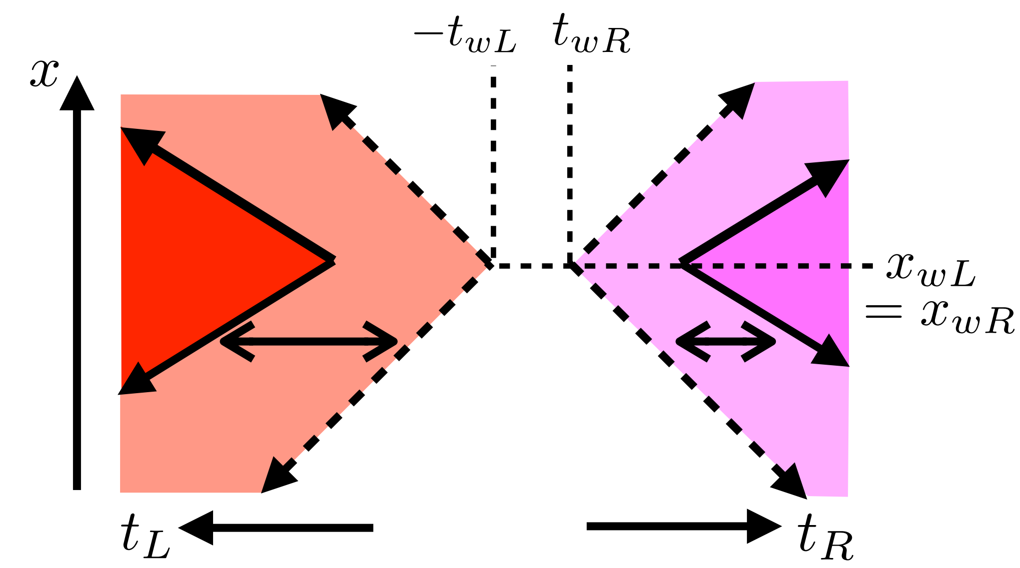
- We have the same 4 regimes as before:



Prediction

(head-on, d=2)





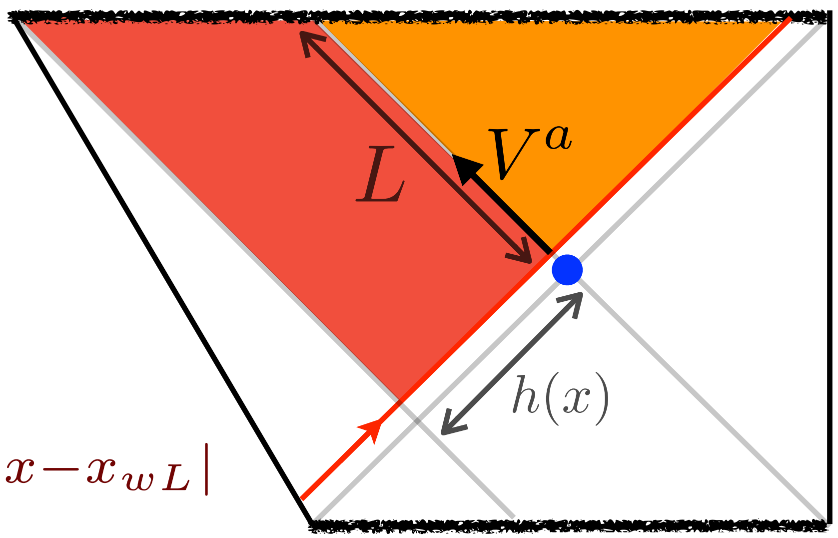
$$x_{wL} = x_{wR} = 0\,,\ t_{wL} = -50$$
$$\delta S_1 = 1\,,\ \delta S_2 = \sqrt{S}$$

- Small Δt: checked linear growth of Vol(x) numerically for localised shocks in planar/hyperbolic black holes
- Large Δt: ?

Late time regime in gravity

- At late times: derive **upper bound** on volume using **Raychaudhuri eq.**

  - Single shock:



$$ds^2 = -\frac{4\ell^2}{(1+u\bar{v})^2}\,du\,dv + r_H^2\left(\frac{1-u\bar{v}}{1+u\bar{v}}\right)^2 d\vec{x}^2$$

$$\bar{v} = v + \Theta(u)h(x) \qquad h(x) \sim \frac{\delta S_1}{S}\, e^{-t_{wL} - \frac{1}{v_B}|x - x_{wL}|}$$

Raychaudhuri: $$\dot{\theta} = -\frac{\theta^2}{d-1} - \sigma^2 + \omega^2 - R_{ab}K^a K^b + \dot{K}^a{}_{;a}$$

across shock: $$T_{uu} \sim \delta(u)h(x) \quad \Rightarrow \quad \Delta\theta \sim -h(x)$$

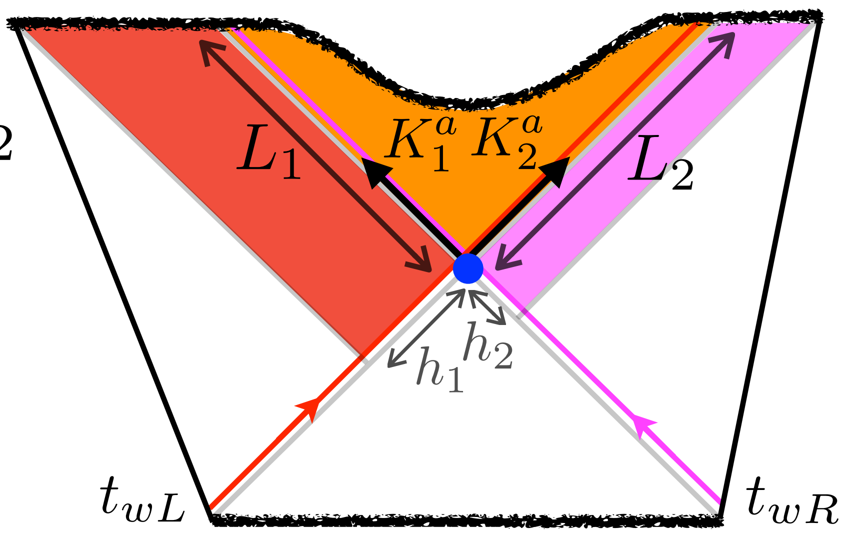
after shock: $$\dot{\theta} \leq -\frac{\theta^2}{d-1} \quad \Rightarrow \quad L \leq -\frac{d-1}{\theta} \sim \frac{1}{h(x)}$$

Late time regime in gravity

- At late times: derive **upper bound** on volume using **Raychaudhuri eq.**

  - Two shocks, ansatz:

$$ds^2_{\text{post-coll.}} \approx -\frac{4\ell^2}{(1+uv)^2}\,du dv + \tilde{r}_H^2(x)\left(\frac{1-uv}{1+uv}\right)^2 d\vec{x}^2$$



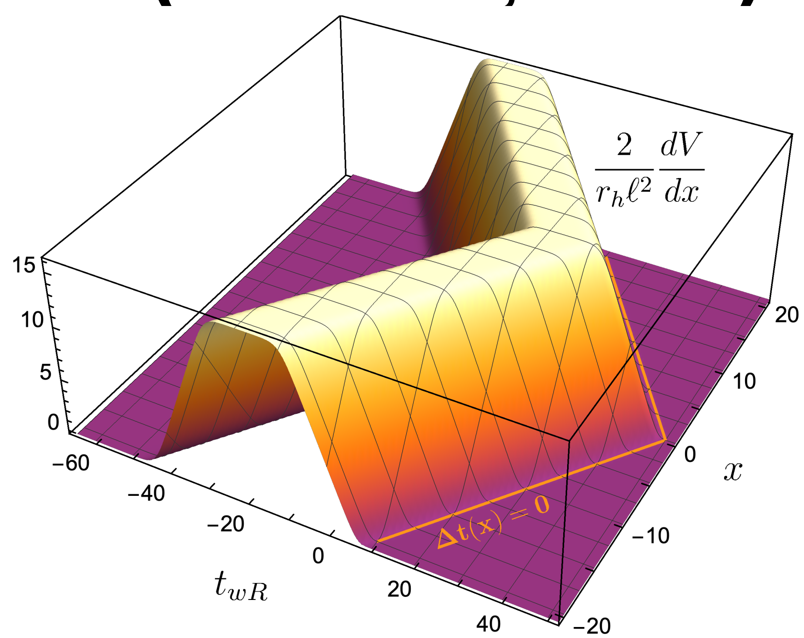
strength of collision: $h_1(x)h_2(x) \sim \frac{\delta S_1\, \delta S_2}{S^2}\, e^{\Delta t(x)}$

Raychaudhuri => $L_1 L_2 \leq \frac{\ell^2}{h_1(x)h_2(x)}$

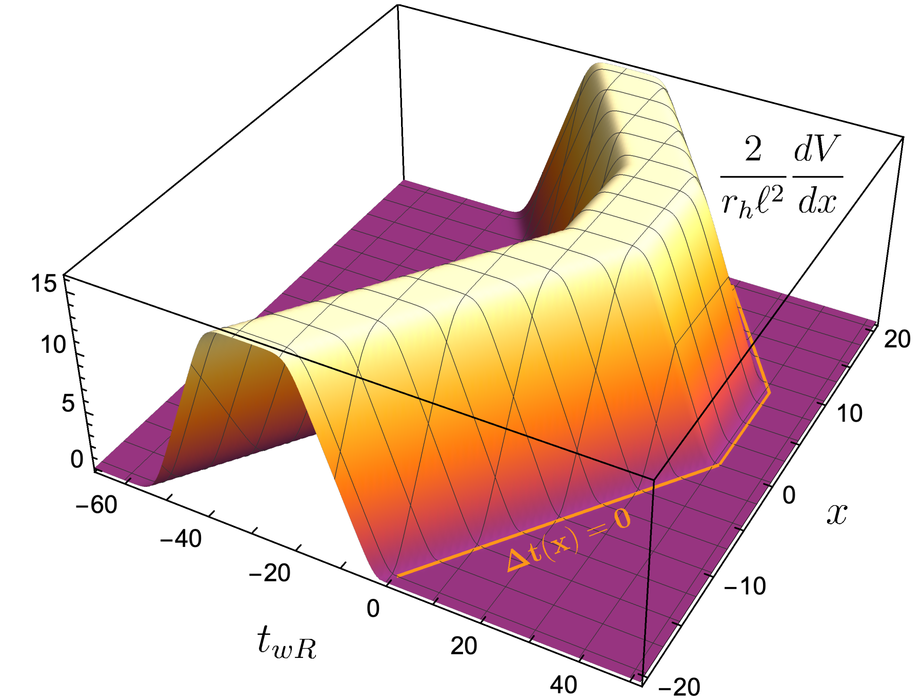
=> analytical upper bound on Vol(post-collision)

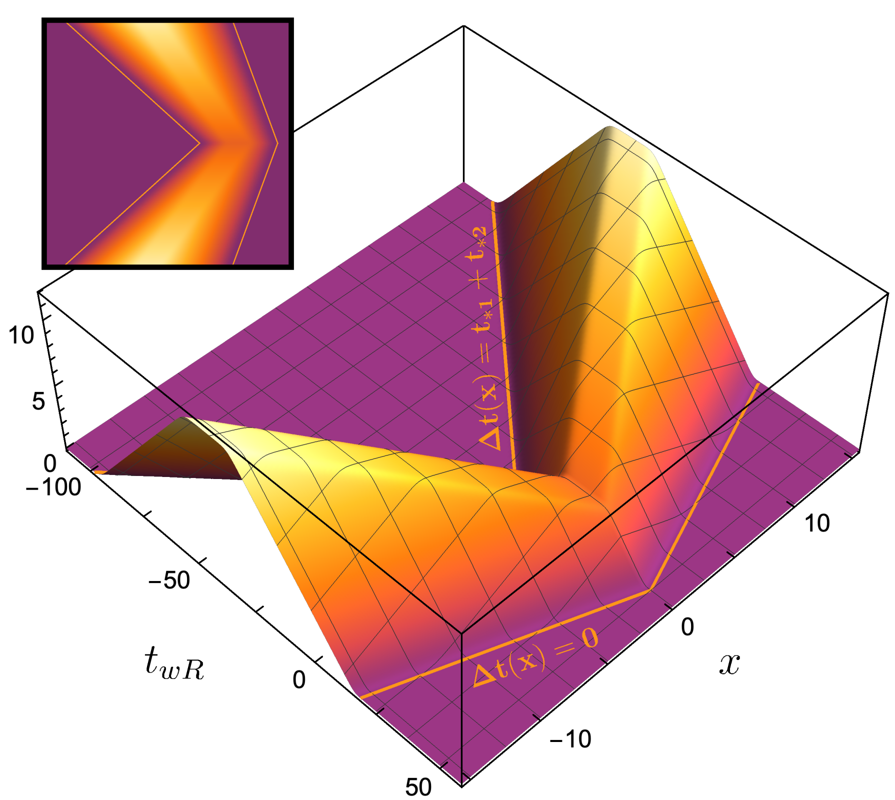
Gravity upper bound vs. circuit prediction

(head-on, AdS3)

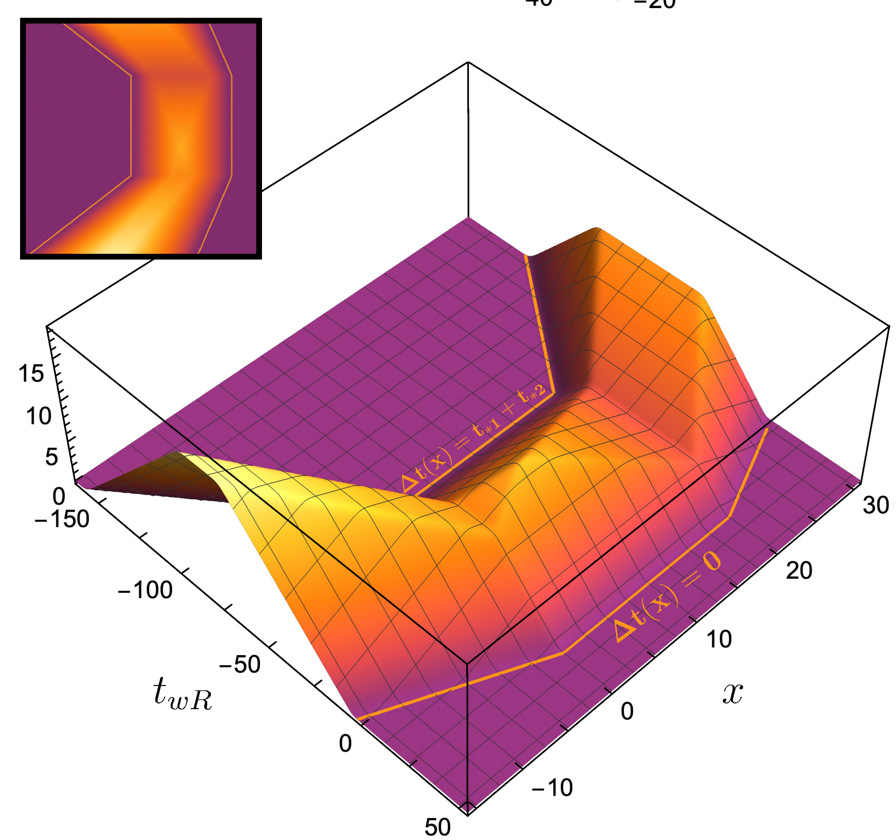


(finite impact parameter, AdS3)





(head-on, AdS5)



(finite impact parameter, AdS5)

Operator size

Operator size

- Spread of perturbation through circuit: "growth" of an operator
- Make this more precise
- Toy model: Sachdev-Ye-Kitaev quantum mechanics

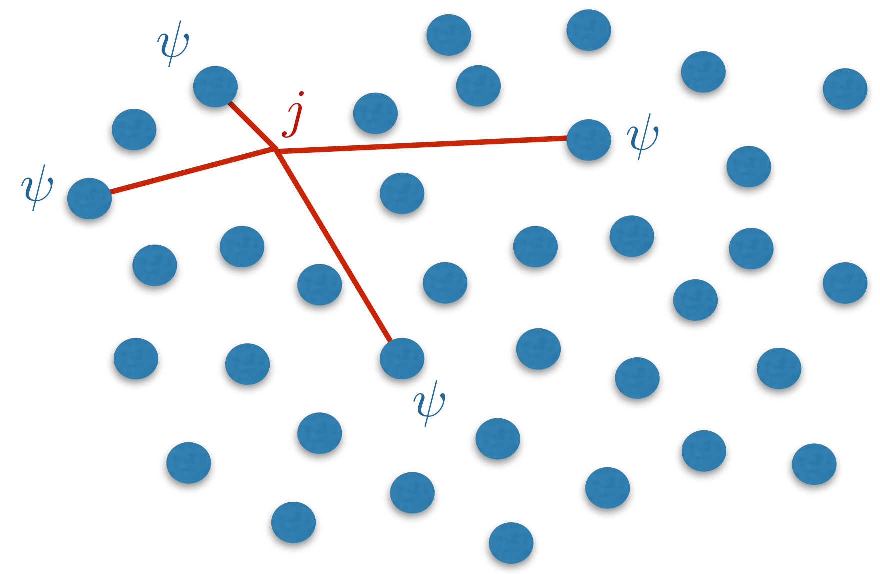
  - N Majorana fermions with random, Gaussian all-to-all couplings
  - Emergent conformal symmetry (time reparametrizations $\tau \to f(\tau)$) in the IR
  - Symmetry is spontaneously & explicitly broken. Effective action for Goldstone:

$$I_{\text{eff.}}[f] \propto -\frac{N}{J} \int d\tau \, \text{Schw}(f(\tau), \tau)$$

  - Same action describes AdS2 dilaton gravity

$$H = -\sum_{ijkl}^{N} j_{ijkl} \, \psi_i \psi_j \psi_k \psi_l$$

$$\overline{j_{ijkl}} = 0 \, , \quad \overline{j_{ijkl}^2} = J^2/N^3$$



[Sachdev/Ye '93] [Kitaev '15]
[Maldacena/Stanford '16] ...

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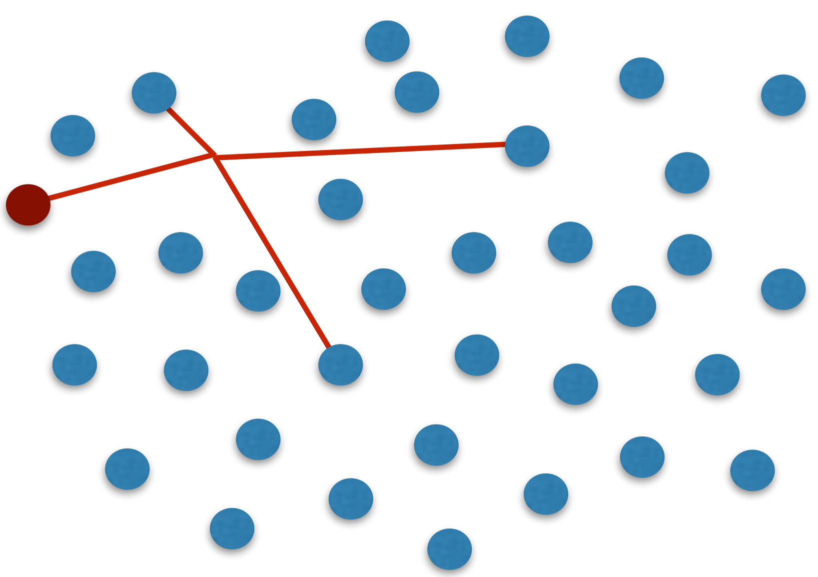

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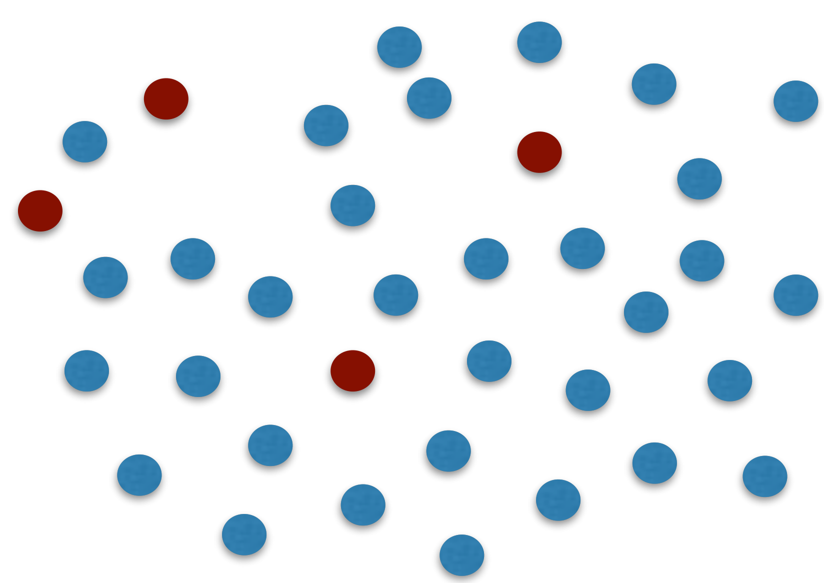

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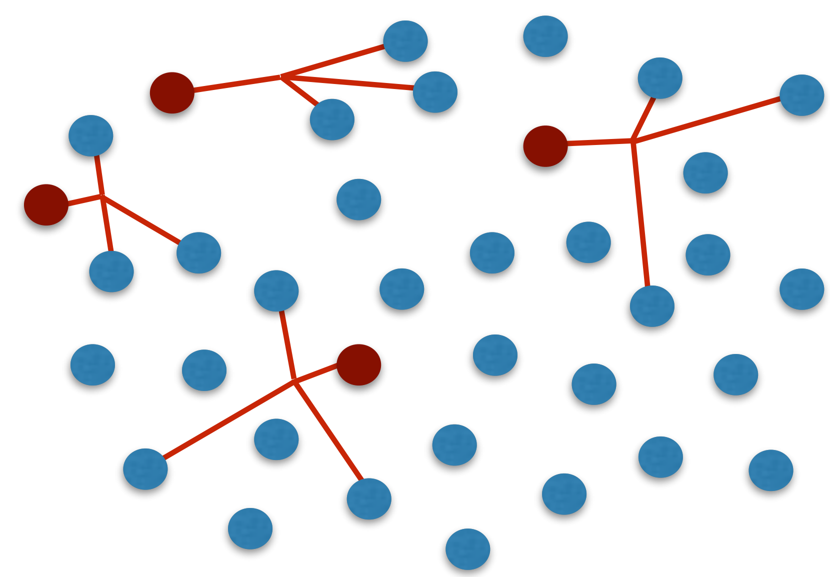

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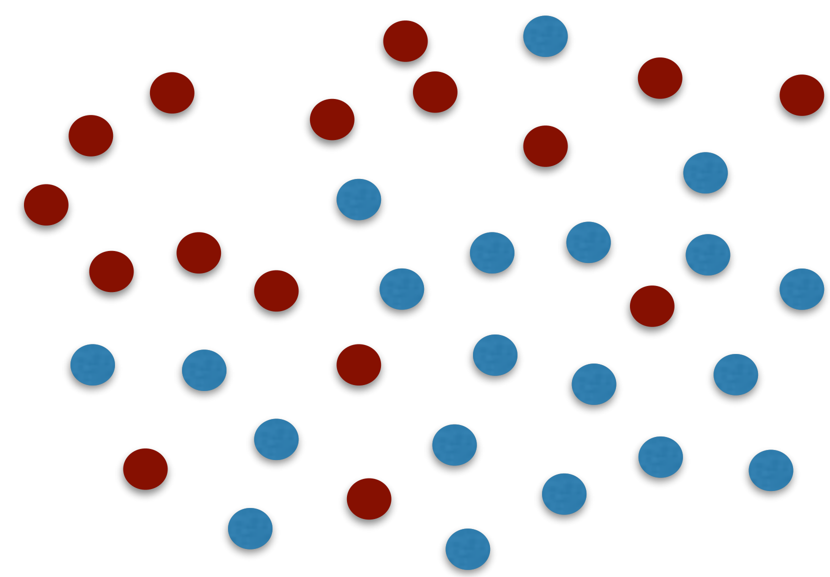


[Sachdev/Ye '93] [Kitaev '15]

[Maldacena/Stanford '16] ...

Operator size in SYK

- Orthogonal operator basis: $\Gamma_{i_1 \cdots i_k} = i^{\frac{k(k-1)}{2}} \psi_{i_1} \cdots \psi_{i_k}$ $\quad (i_1 < \ldots < i_k\,, \quad \{\psi_i, \psi_j\} = 2\delta_{ij})$
- Canonically purify the system: $\psi_i \to \psi_i^R,\, \psi_i^L$

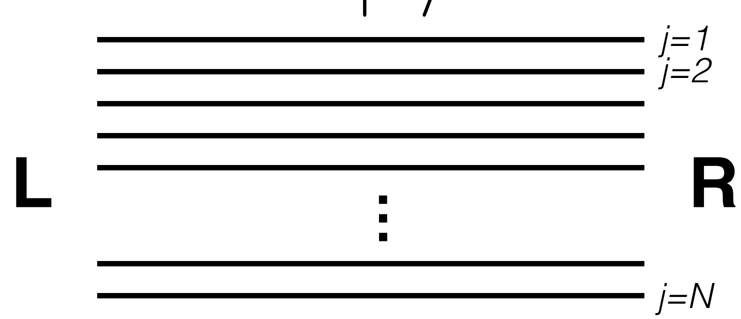
  "qubit" basis: $c_j = \frac{1}{2}(\psi_j^L + i\psi_j^R)$ $\quad \{c_j, c_k\} = \{c_j^\dagger, c_k^\dagger\} = 0\,, \quad \{c_j, c_k^\dagger\} = \delta_{jk}$

  maximally entangled state: $c_j|0\rangle = 0 \quad \forall j$

- "Size operator": $\hat{n}_\infty \equiv \sum_{j=1}^{N} c_j^\dagger c_j$ [Qi/Streicher '18]

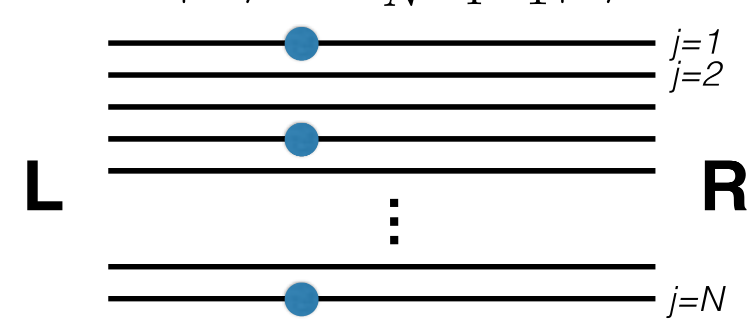
$$\langle \mathcal{O} | \hat{n}_\infty | \mathcal{O} \rangle = \#\,\text{flavors contained in } \mathcal{O}$$

$|0\rangle$



$\Rightarrow \langle 0 | \hat{n}_\infty | 0 \rangle = 0$

$|\Psi\rangle \equiv c_N^\dagger c_4^\dagger c_1^\dagger |0\rangle$



$\Rightarrow \langle \Psi | \hat{n}_\infty | \Psi \rangle = 3$

- Similar construction exists in more general models [Gu/Kitaev/Zhang '21]

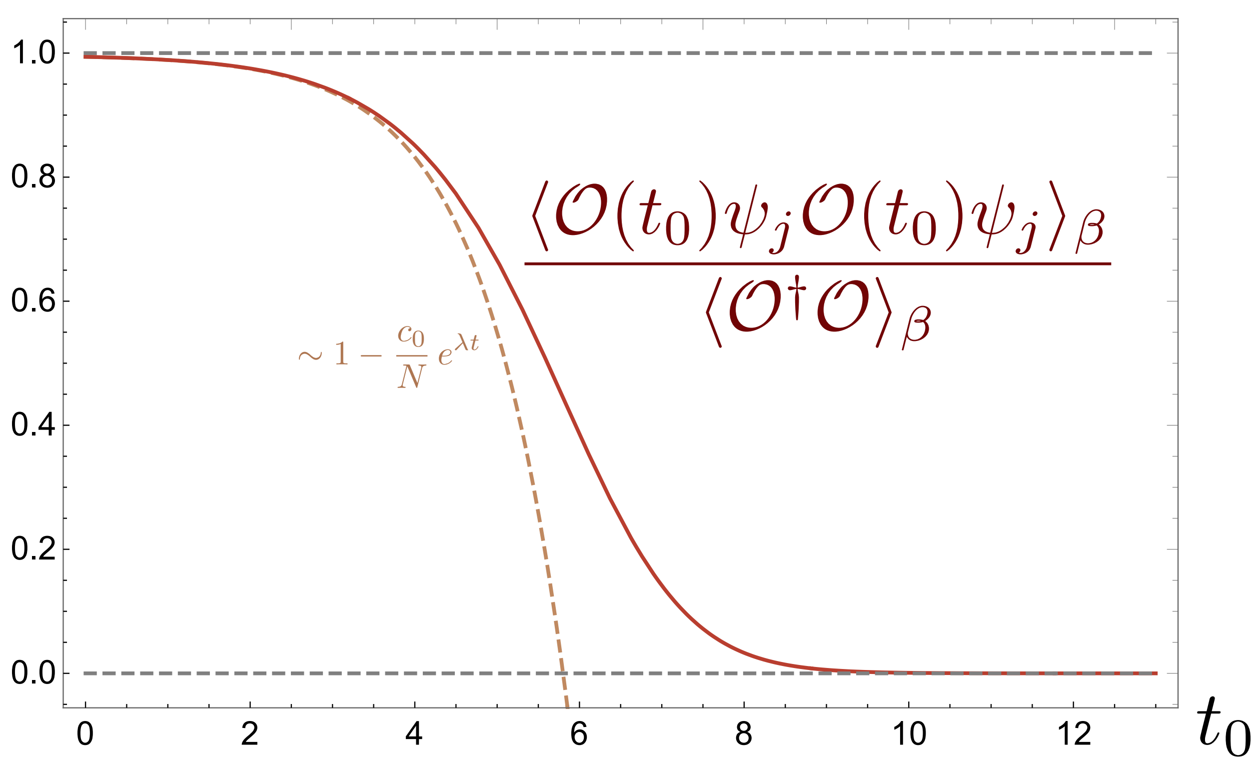
- Generalize to thermal state: $\langle \mathcal{O} | \hat{n}_\beta | \mathcal{O} \rangle = \langle \mathrm{TFD} | \mathcal{O}^\dagger \, \hat{n}_\infty \mathcal{O} | \mathrm{TFD} \rangle$ (up to regularisation)

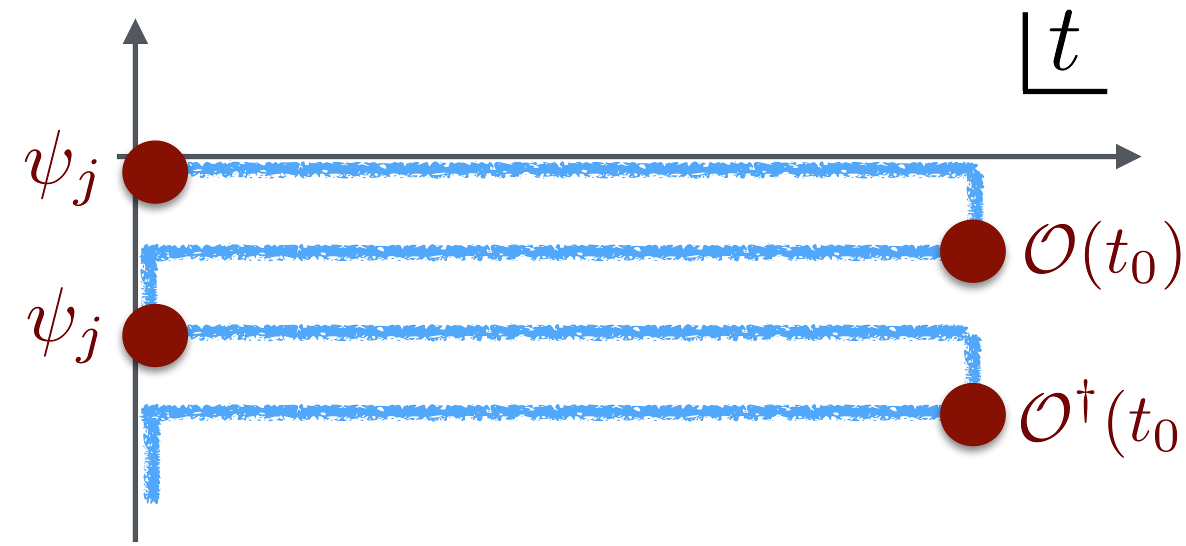
- Explicit evaluation shows: $$\frac{\langle \mathcal{O} | \hat{n}_\beta | \mathcal{O} \rangle}{\langle \mathcal{O}^\dagger \mathcal{O} \rangle_\beta} = n_{\max} \left[1 - \frac{1}{N} \sum_{j=1}^{N} \frac{\langle \mathcal{O}(t_0) \psi_j \mathcal{O}(t_0) \psi_j \rangle_\beta}{\langle \mathcal{O}^\dagger \mathcal{O} \rangle_\beta} \right]$$

"out-of-time-order" correlation function

- OTOCs received a lot of attention as measures of quantum chaos
  [Larkin/Ovchinnikov '68] [Kitaev '14] [Shenker/Stanford '14] … [FH/Rozali '18] …

- They exhibit **exponential growth** when $t_0 \sim \beta \log(N)$, then saturate

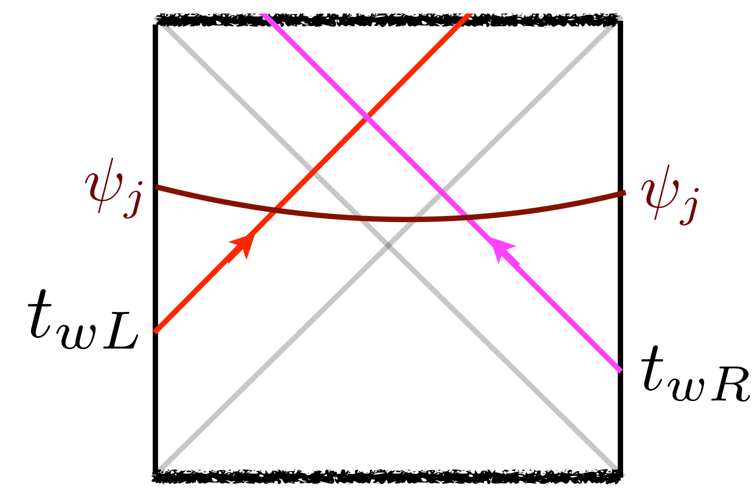




- "Epidemic" operator growth in quantum circuit matches more detailed OTOC calculations in SYK, Schwarzian, CFTs, …

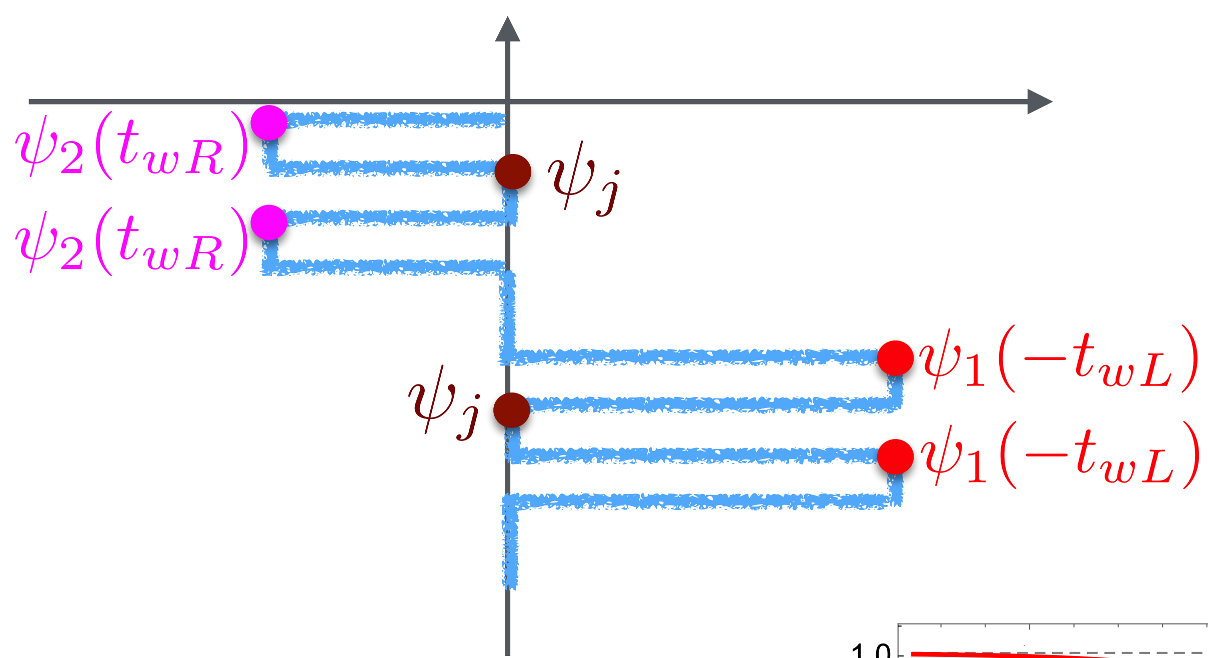
Interior collisions and OTOCs

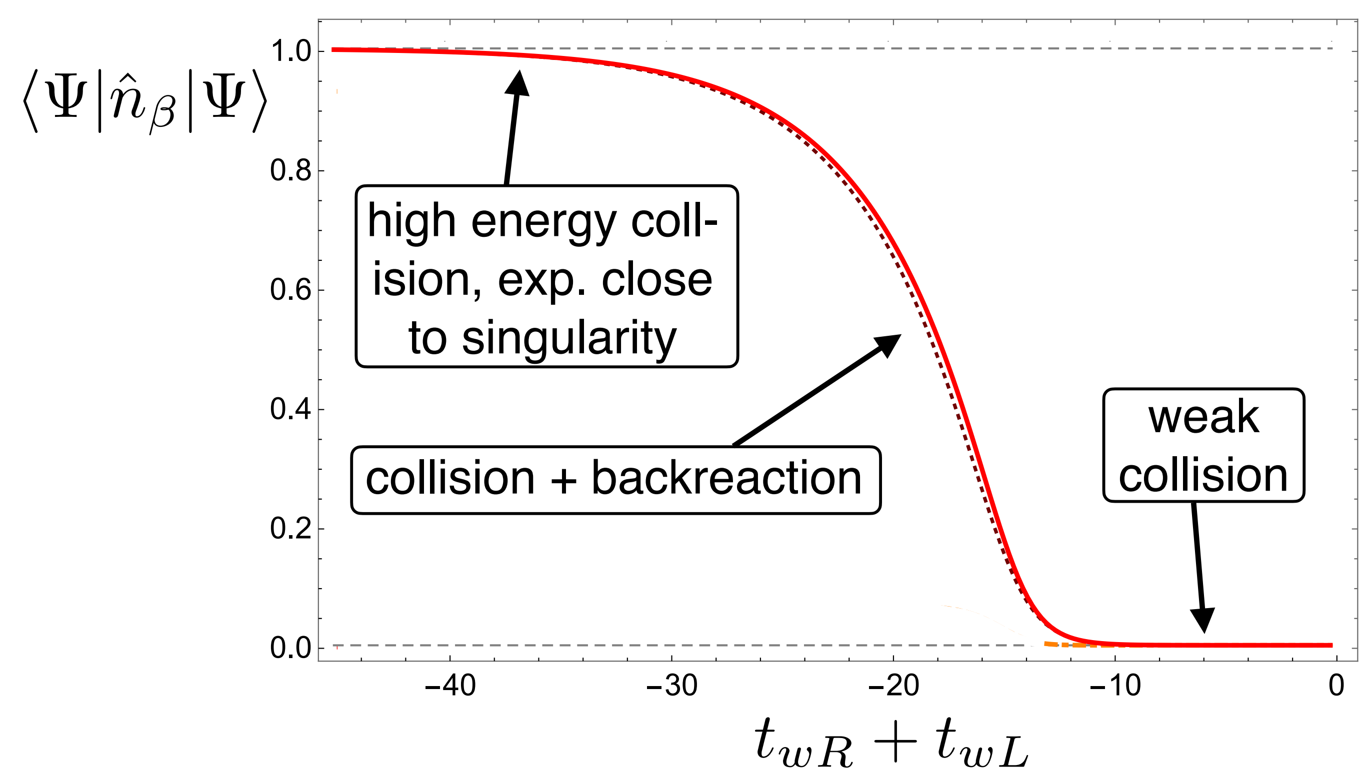
- Apply this formalism to our collision setup:



$$|\Psi\rangle \equiv \psi_1^L(t_{wL})\psi_2^R(t_{wR})|\mathrm{TFD}\rangle$$

$$\langle\Psi|\hat{n}_\beta|\Psi\rangle :$$





- <u>Proposal:</u> this 6-point OTOC computes the “size” of the double perturbation. It matches the fraction of healthy gates in the corresponding circuit.

[FH/Zhao ’21] [FH/Streicher/Zhao ’21]

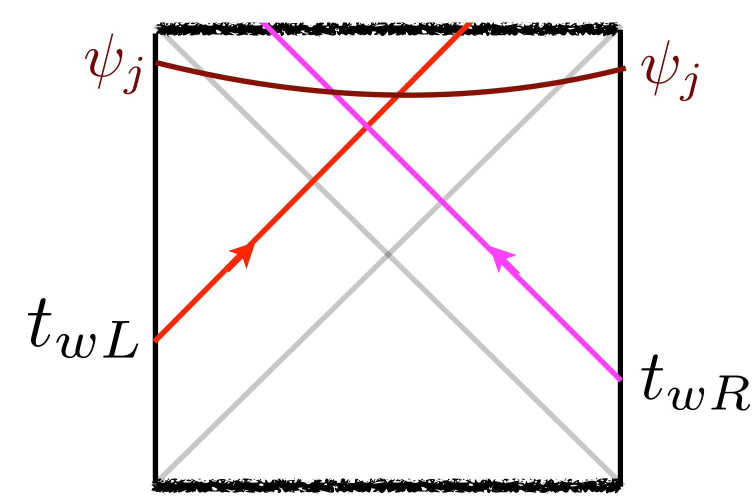
Summary & Outlook

Summary

- Entanglement & other information theoretic concepts: emergence of local spacetime dynamics in AdS/CFT

- Probe connection between interior geometry and L/R entanglement:

strong collision => { • disrupt L/R entanglement • decorrelate $\langle \mathrm{TFD} | \psi_j^L \psi_j^R | \mathrm{TFD} \rangle$ • "remove" interior geometry }



- Quantum circuit model captures non-linear gravity effects, two-sided correlation functions, operator growth

Questions

- Quantum circuit is coarse-grained representation of geometry (scale ℓ_{AdS}). Can we refine it?
  - Derive local Einstein equations?
- Spacetime volume is an unusual way to characterize a scattering process. Make connection with S-matrix?
- Two-sided setup was crucial (TFD, operator size, …). How to deal with one-sided black holes, or pure states?
- How to define operator size in CFTs, QFTs, …?