# The python's lunch and complexity of decoding Hawking radiation

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# Overview

- **Part One:** Introduction to holography and quantum information

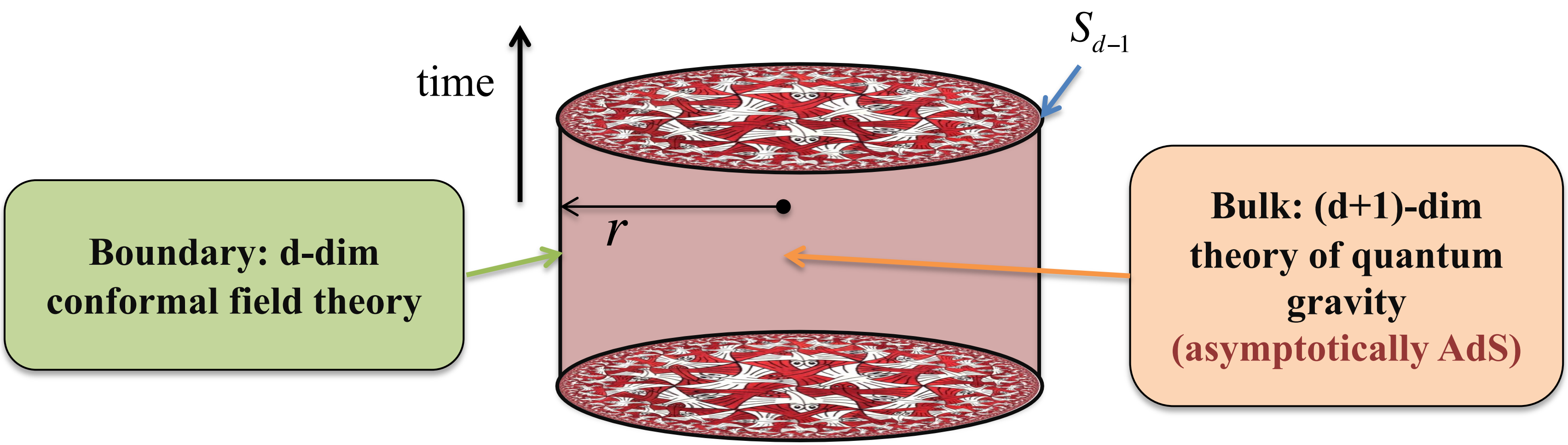
- **Part Two:** The python's lunch: geometric obstructions to decoding Hawking radiation

*Adam Brown, HG, Geoff Penington, Leonard Susskind;* ***arXiv: 1912.00228***

# Part One

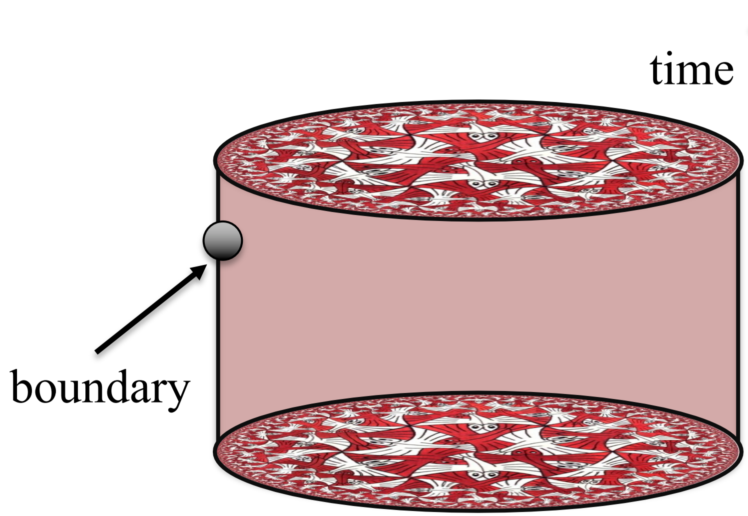
**Introduction to holography and quantum information**

# Holography: AdS/CFT Correspondence



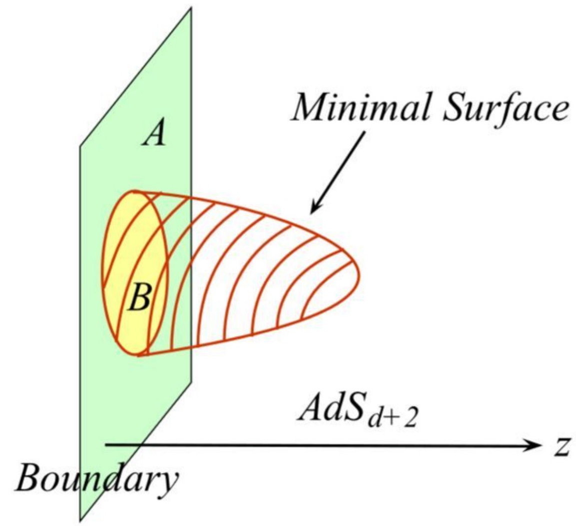

Example: N=4 Super-Yang-Mills = Type IIB string theory in $AdS_5 \times S_5$
[Maldecena'97]

# Holography and quantum information




**1. Entanglement entropy = Area**

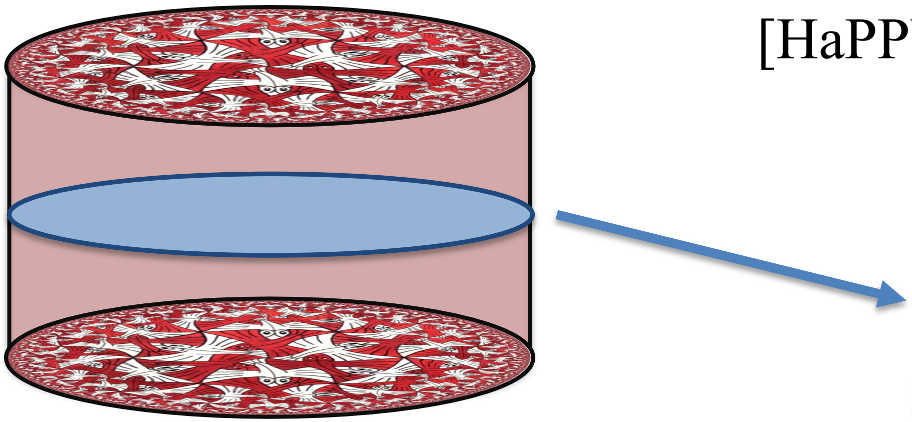
[Ryu-Takayanagi 2006]



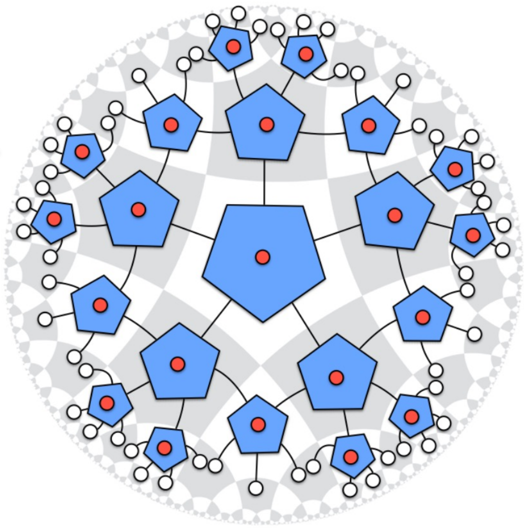

***there is covariant version**

***as well as generalized entanglement, including bulk entanglement**

# Holography and quantum information



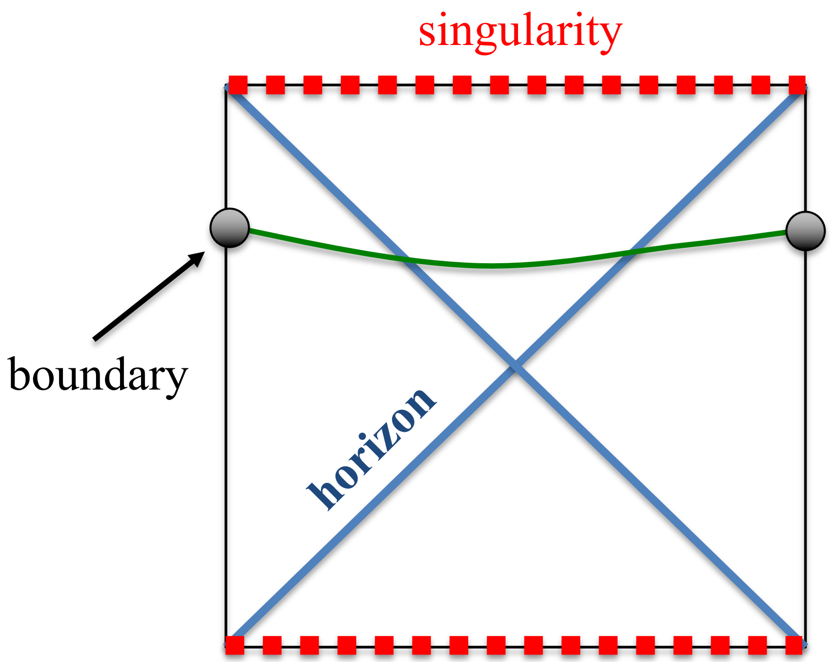
**2. Error correction= Space-like slice**
[HaPPY paper 2015]



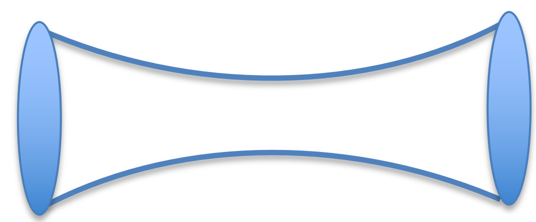
***Operator reconstruction**

***Derivation of the Page curve**

# Holography and quantum information



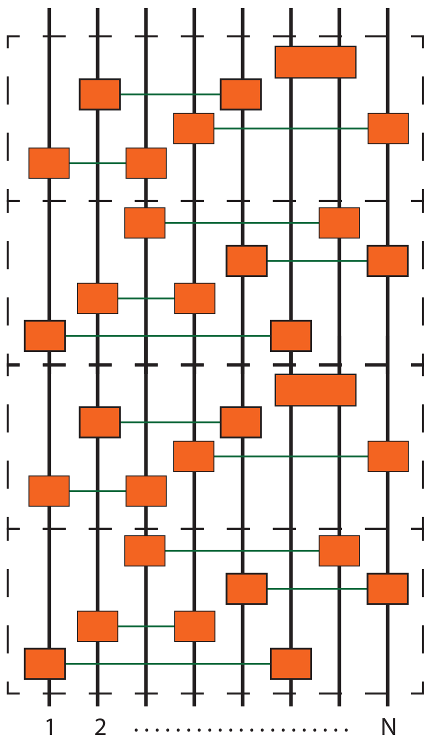

**3. Complexity= Volume/Action**
[Susskind and collaborators 2014]



$$\mathcal{C}(|\psi(t_L, t_R)\rangle) \propto \frac{V}{\hbar G l_{AdS}}$$

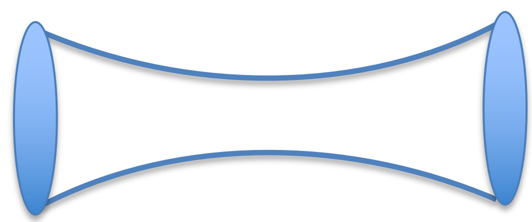
# Holography and quantum information

$$|\psi(t_L, t_R)\rangle$$




$$|000\cdots000\rangle$$

**3. Complexity= Volume/Action**
[Susskind and collaborators 2014]



$$\mathcal{C}(|\psi(t_L, t_R)\rangle) \propto \frac{V}{\hbar G l_{AdS}}$$

# Part Two

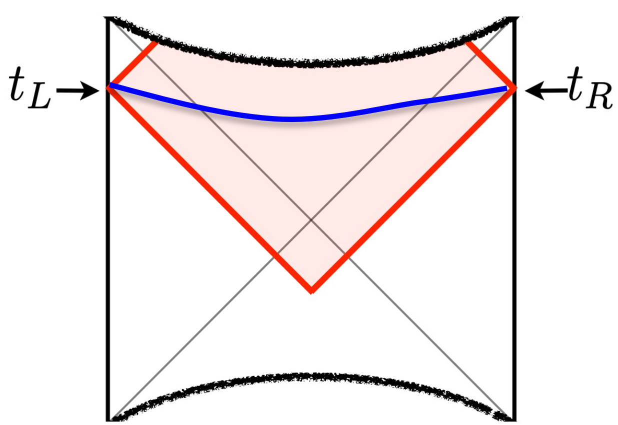
**Complexity of evaporating black hole and the python's lunch geometry**

[Based on **arXiv: 1912.00228]**

# Relationship between complexity and geometry

A. Brown, D. Roberts, L. Susskind, B. Swingle, Y. Zhao
*"Complexity Equals Action"; arXiv: 1509.07876*

D. Stanford, L. Susskind,
*"Complexity and Shock Wave Geometries"; arXiv: 1406.2678*




[Myers and collaborators]

$$|\psi(t_L, t_R)\rangle$$

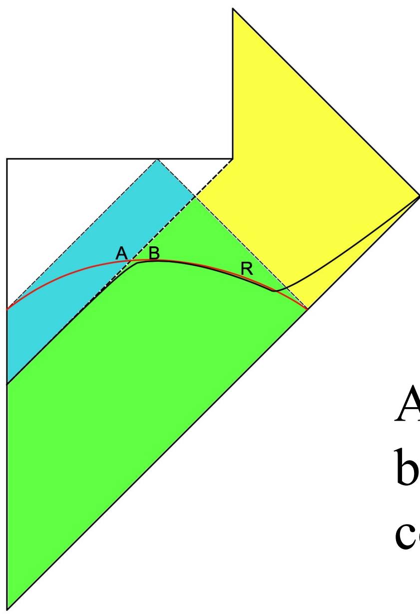
**State Complexity = Volume of ER Bridge**

**State Complexity = Action of WDW Patch**

# Decoding Hawking radiation is exponentially hard

Daniel Harlow, Patrick Hayden,

*" Quantum Computation vs. Firewalls"; arXiv:1301.4504*




Decoding the information that fell into black hole by only action on radiation is hard.

$$\text{Complexity} \sim e^{S}$$

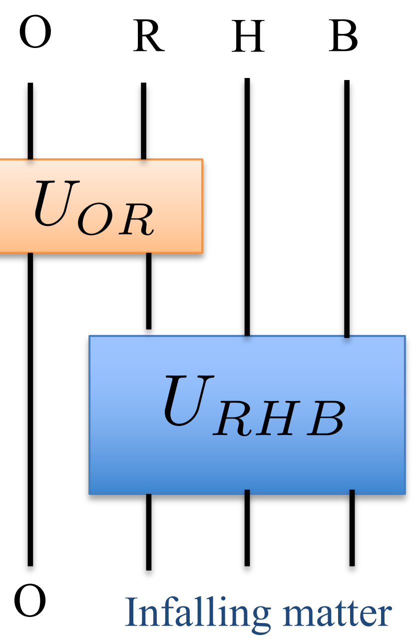
Argument relies on the mixing assumption of black hole and radiation as well as complexity class reduction.

[Harlow-Hayden 2013; Aaronson 2014]

# Hawking radiation is pseudorandom (2019)

I. Kim, E. Tang, J. Preskill,

*" The ghost in the radiation: Robust encodings of black hole interior"; arXiv:2003.05451*




- RB radiation state is pseudorandom
- Computationally bounded observer O cannot destruct encoding of A in RB system.
- Implies that decoding Hawking radiation required exponential complexity

$$\text{complexity} \sim e^{S}$$

[Kim, Tang, Preskill et. al 2020]

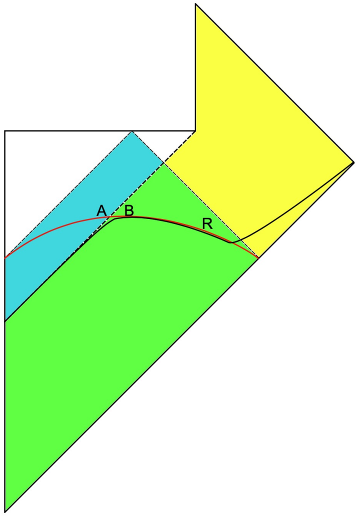
# Apparent contradiction

*For evaporating black hole volume/action is polynomial and those complexity is polynomial.*

**ploy(S)**

*Harlow and Hayden suggested it is exponentially hard to decode the radiation.*

**exp(S)**

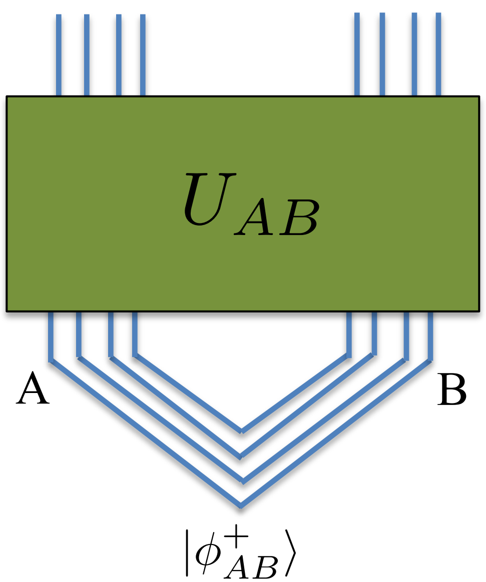



***Where is this contradiction coming from?***

# Restricted vs unrestricted complexity

We are talking about two different notions of complexity

\- - - - - - unrestricted vs restricted - - - - - -




**Unrestricted complexity**

$$U_{AB} = g_1 g_2 \cdots g_C$$

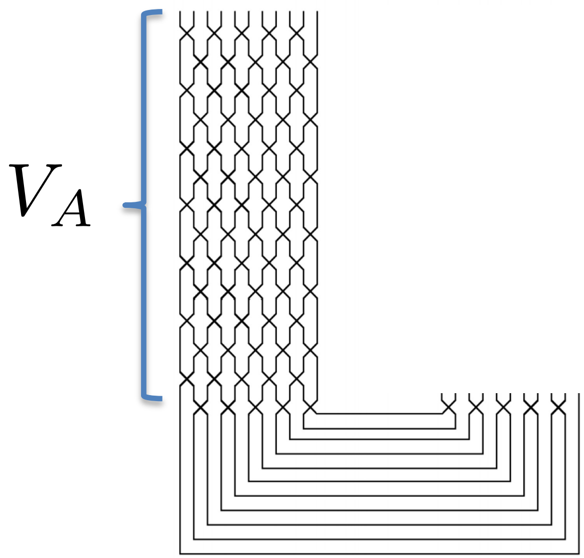
**Restricted complexity**

$$V_A = g_1 g_2 \cdots g_{C_A}$$

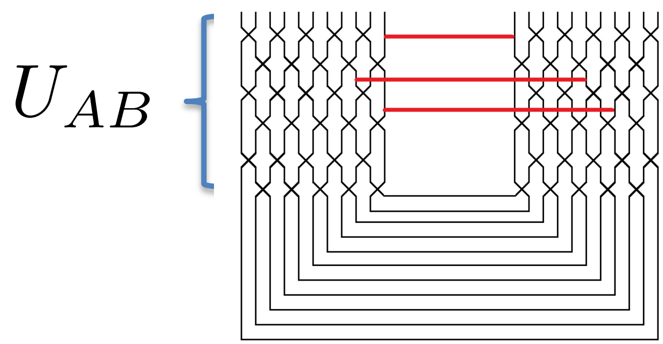
$$\boxed{V_A|\phi^+_{AB}\rangle \approx U_{AB}|\phi^+_{AB}\rangle}$$

# Restricted vs unrestricted complexity

Restricted Complexity
(Harlow-Hayden)




Unrestricted Complexity
(Volume/Action)



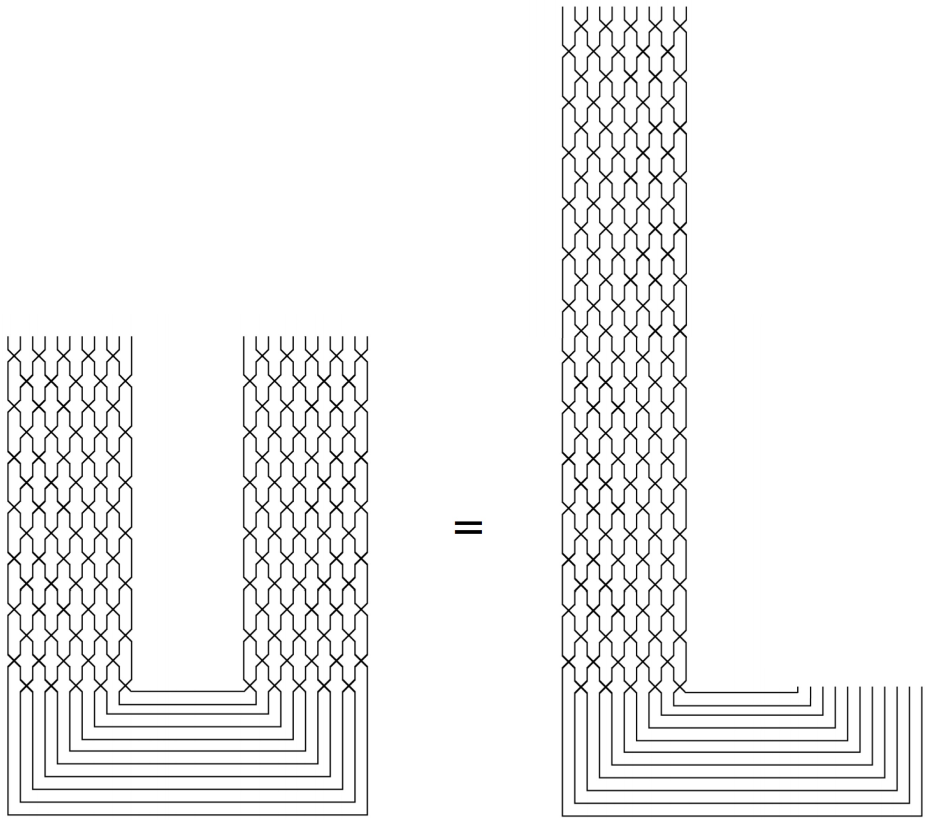
# When are restricted and unrestricted complexities very different?

**Time evolution of the**
**thermofield double.**

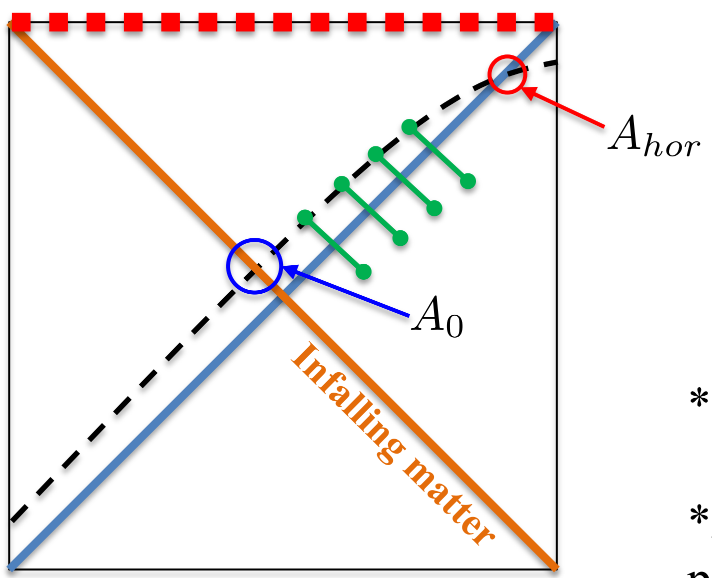
***Restricted Complexity***

**=**

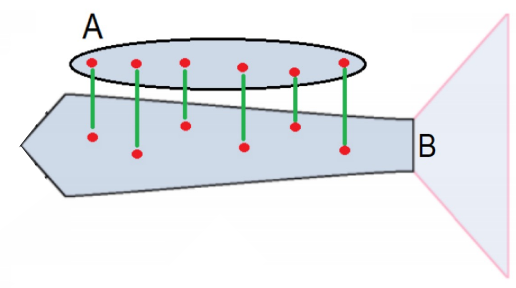
***Unrestricted Complexity***



# Cauchy slice of the evaporating black hole




**“Nice” Cauchy slice**



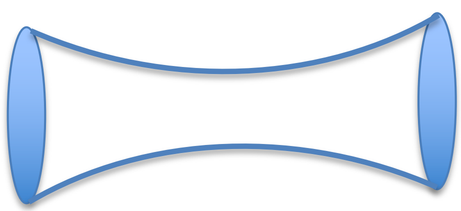

*Radiation and black hole modes are **coupled**!

*A bit after **Page time**, volume/action is polynomial in **S**.

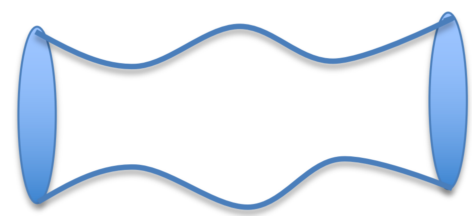
*Restricted complexity is **exponential**.

# When are restricted and unrestricted complexities very different?

**Small (polynomial) restricted complexity**



**Large (exponential) restricted complexity**



**Time evolved thermo field double (TFD)**

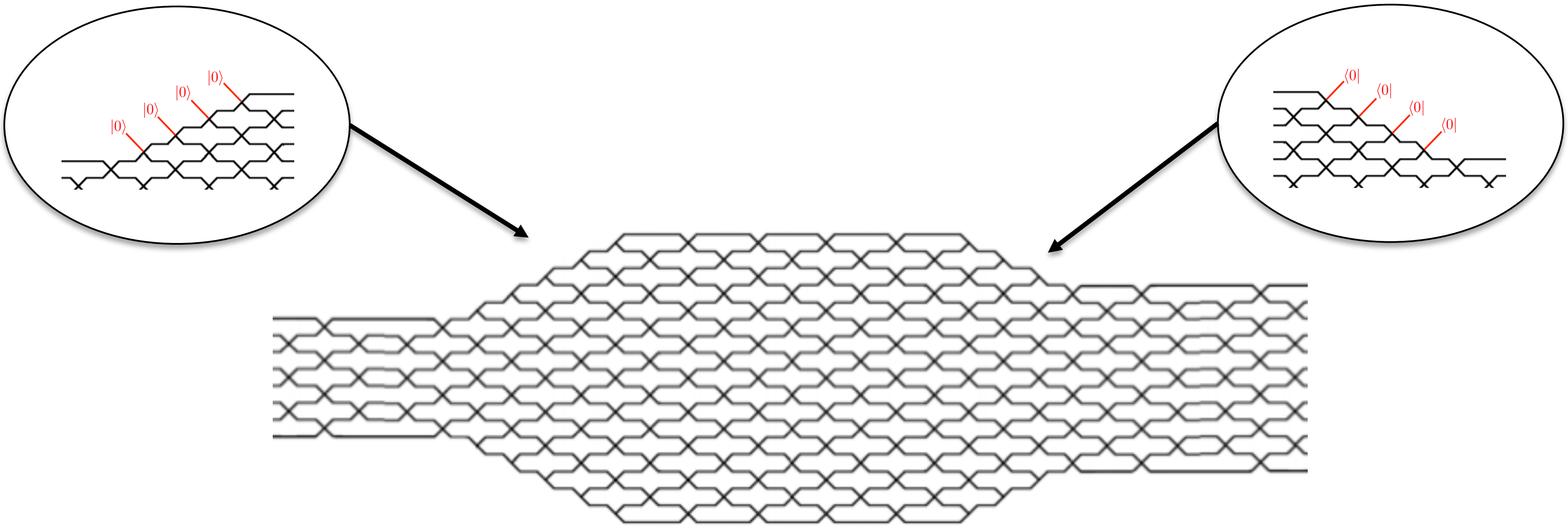
**Python's lunch geometry**

**Evaporating Black Hole**

## When are restricted and unrestricted complexities very different?

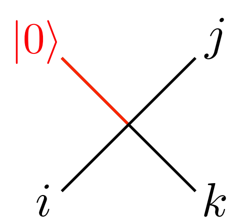
# The python's lunch

# The python's lunch in tensor network (toy model)



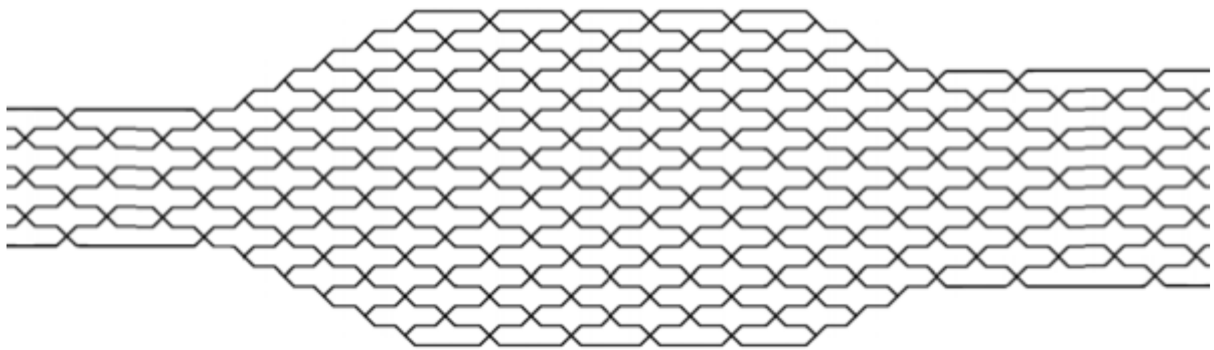

Tensor network is built off **unitary gates** and has **isometries** in endpoints.

Isometry:



# The Python's Lunch in Tensor Network

$|\psi_{in}\rangle$

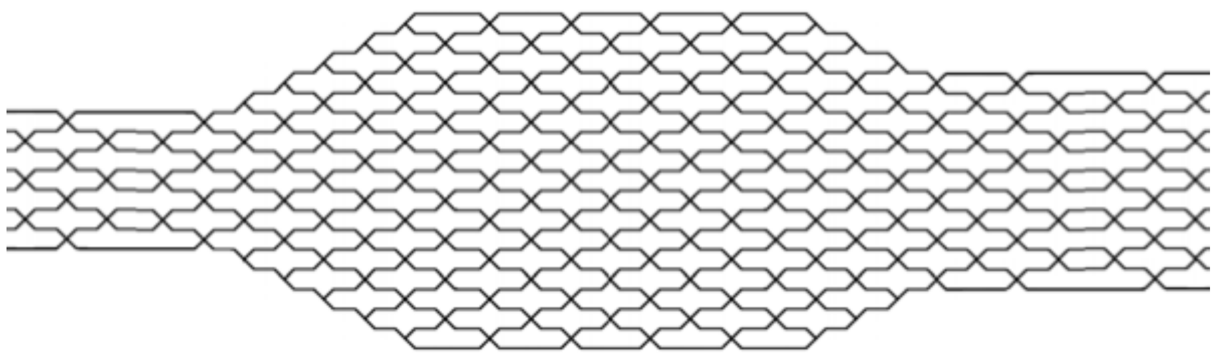


$|\psi_{out}\rangle$

$$|\psi_{out}\rangle \propto \langle 0|^{m_R} \, U_{TN} |\psi_{in}\rangle |0\rangle^{m_L}$$

**Ancillary Input Qubits**

# The Python's Lunch in Tensor Network

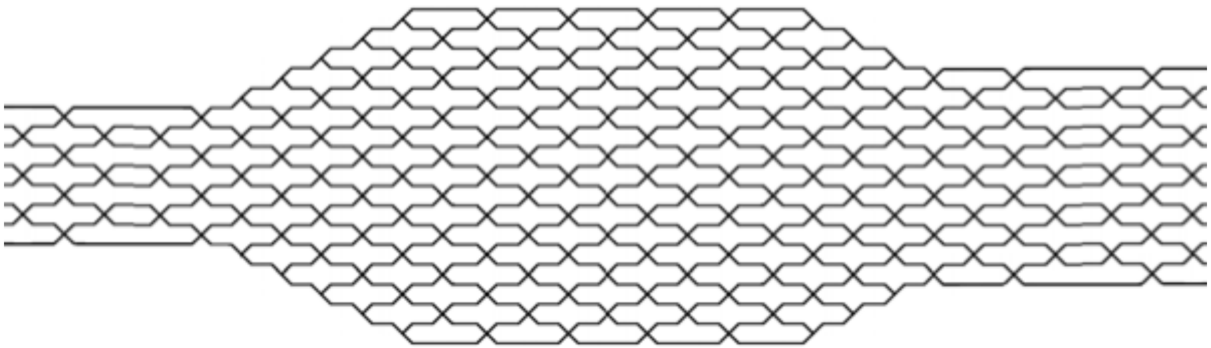
$|\psi_{in}\rangle$  $|\psi_{out}\rangle$

$$|\psi_{out}\rangle \propto \langle 0|^{m_R}\ U_{TN}|\psi_{in}\rangle|0\rangle^{m_L}$$

**Polynomial Complexity Unitary**

**Ancillary Input Qubits**

# The Python's Lunch in Tensor Network

$|\psi_{in}\rangle$  $|\psi_{out}\rangle$

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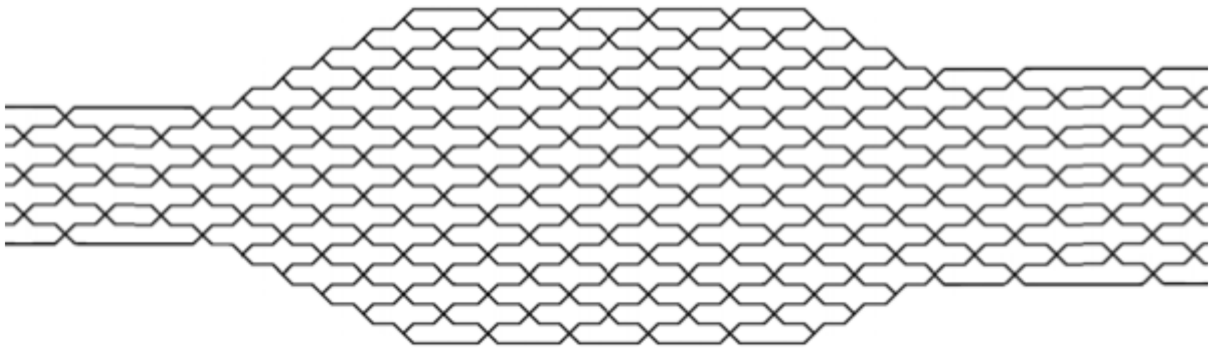
**Post-selection**

**Polynomial Complexity Unitary**

**Ancillary Input Qubits**

# The python's lunch: no post-selection

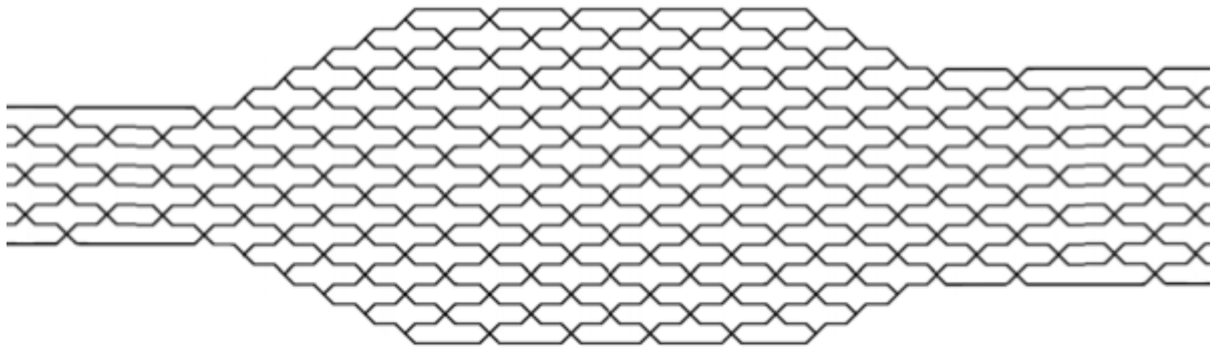
$|\psi_{in}\rangle$  $|\psi_{out}\rangle$

$$|\psi_{out}\rangle|0\rangle^{m_R} = U_{PL}|\psi_{in}\rangle|0\rangle^{m_L}$$

**Unitary**

**Ancillary Input Qubits**

# The python's lunch: no post-selection

$|\psi_{in}\rangle$  $|\psi_{out}\rangle$

$$|\psi_{out}\rangle|0\rangle^{m_R} = U_{PL}|\psi_{in}\rangle|0\rangle^{m_L}$$

**How complex is $U_{PL}$?**

**Unitary**

**Ancillary Input Qubits**

# What's the complexity of removing post-selection / final state projection?

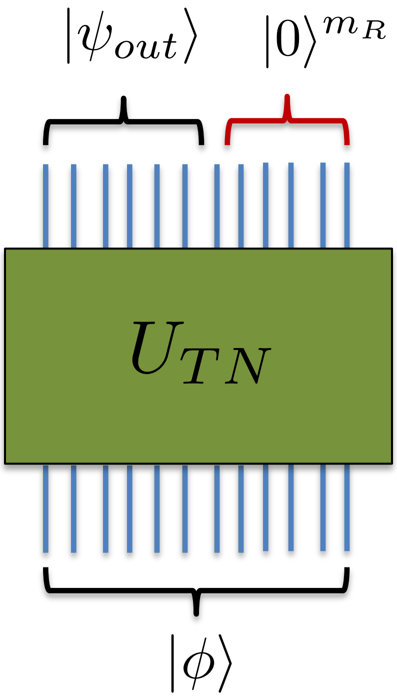
We can measure the qubits and hope to get the right answers.
Probability of the right answer is $1/2^m$ and expected complexity

$$C \propto 2^{m_R} \cdot C_{TN}$$

It is not a fixed unitary and complexity can be improved.

We can do a generalized **Grover-like search.**

# Grover-like search: state dependent

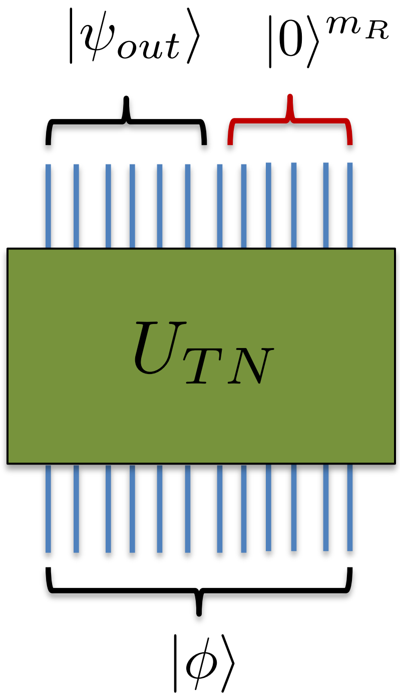



$$U_\phi = 2|\phi\rangle\langle\phi| - I$$

$$V = U_{TN}(2|0\rangle\langle 0|^{m_R} - I)U_{TN}^\dagger$$

[Kitaev - Yoshida 2017]

# Grover-like search: state dependent

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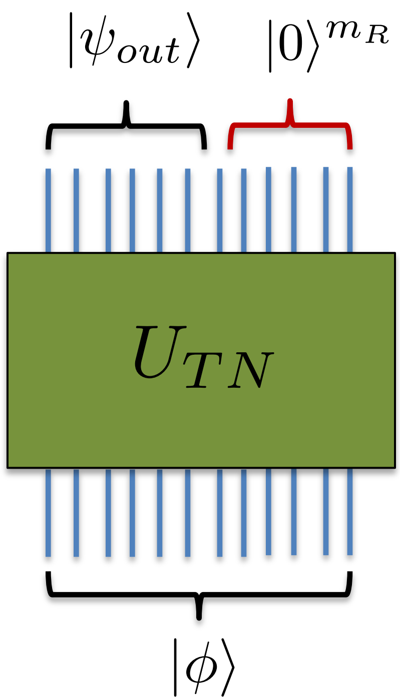
**Repeat sequence:** $U_\phi V$

$l = \sqrt{2^{m_R}}$ **~ times**

# Grover-like search: state dependent

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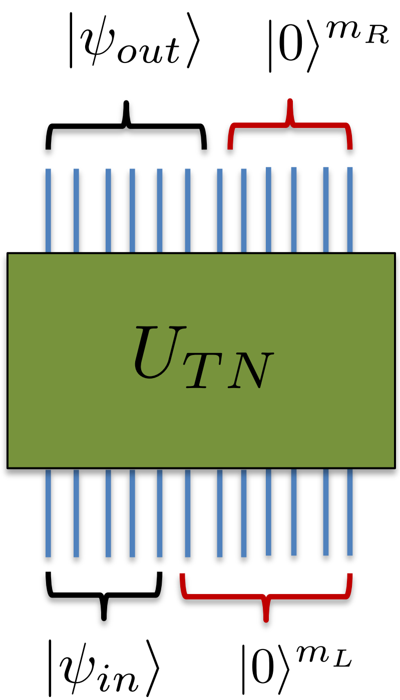
**Repeat sequence:** $U_\phi V$

$l = \sqrt{2^{m_R}}$ **~ times**

$$U_{PL} = U_{TN}\left[U_\phi V\right]^l$$

**This algorithms depends on the state** $|\phi\rangle$

# Grover-like search: state independent




$$U = 2|0\rangle\langle 0|^{m_L} - I$$
$$V = U_{TN}(2|0\rangle\langle 0|^{m_R} - I)U_{TN}^{\dagger}$$

$$U_{PL} = U_{TN}\left[UV\right]^{l}$$

$$\boxed{\mathcal{C}(U_{PL}) \propto \sqrt{2^{m_R}} \cdot C_{TN}}$$

[Berry et. al 2015, Gilyen et. al 2017]

# Is Grover search the optimal strategy?

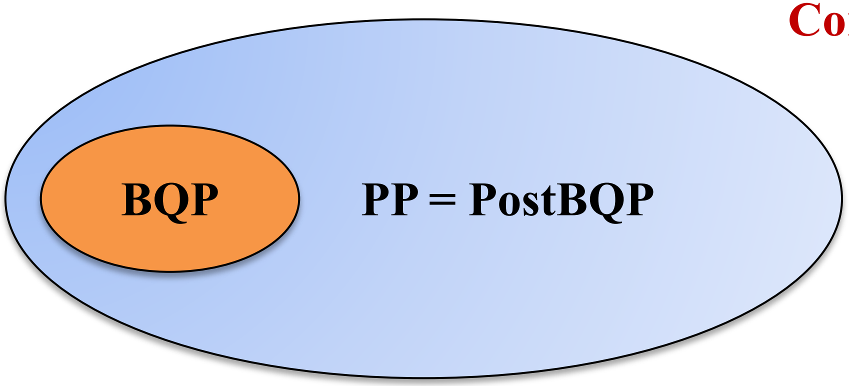
In special cases, for a specific unitary there might be an algorithm that can do better than Grover-like search.

# Is Grover search the optimal strategy?

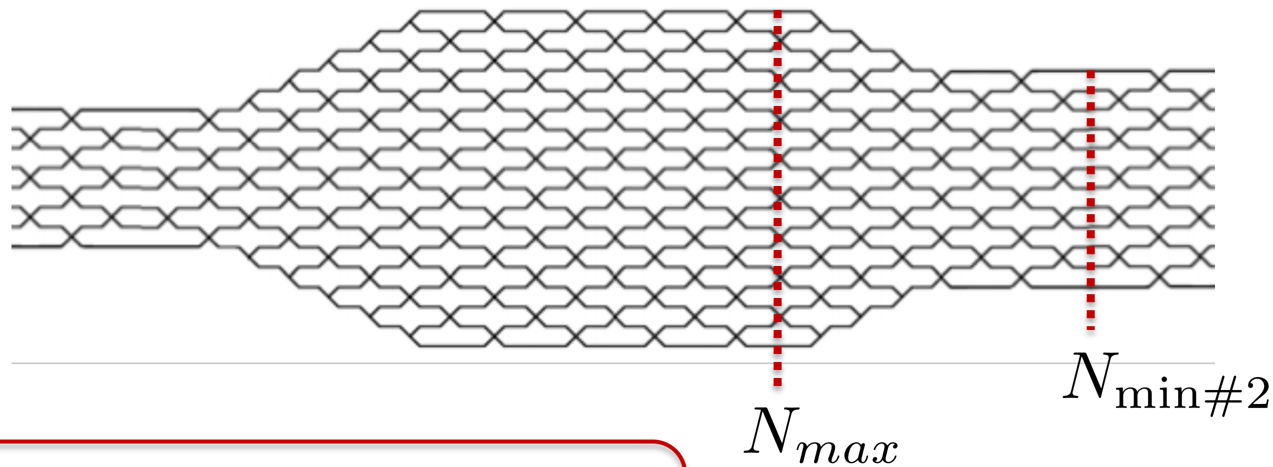
In special cases, for a specific unitary there might be an algorithm that can do better than Grover-like search.

However, for generic, **scrambling tensor network** $U_{TN}$ polynomial algorithm is extremely unlikely to exist.

**Complexity class collapse!**



# Conjecture: restricted complexity in tensor network



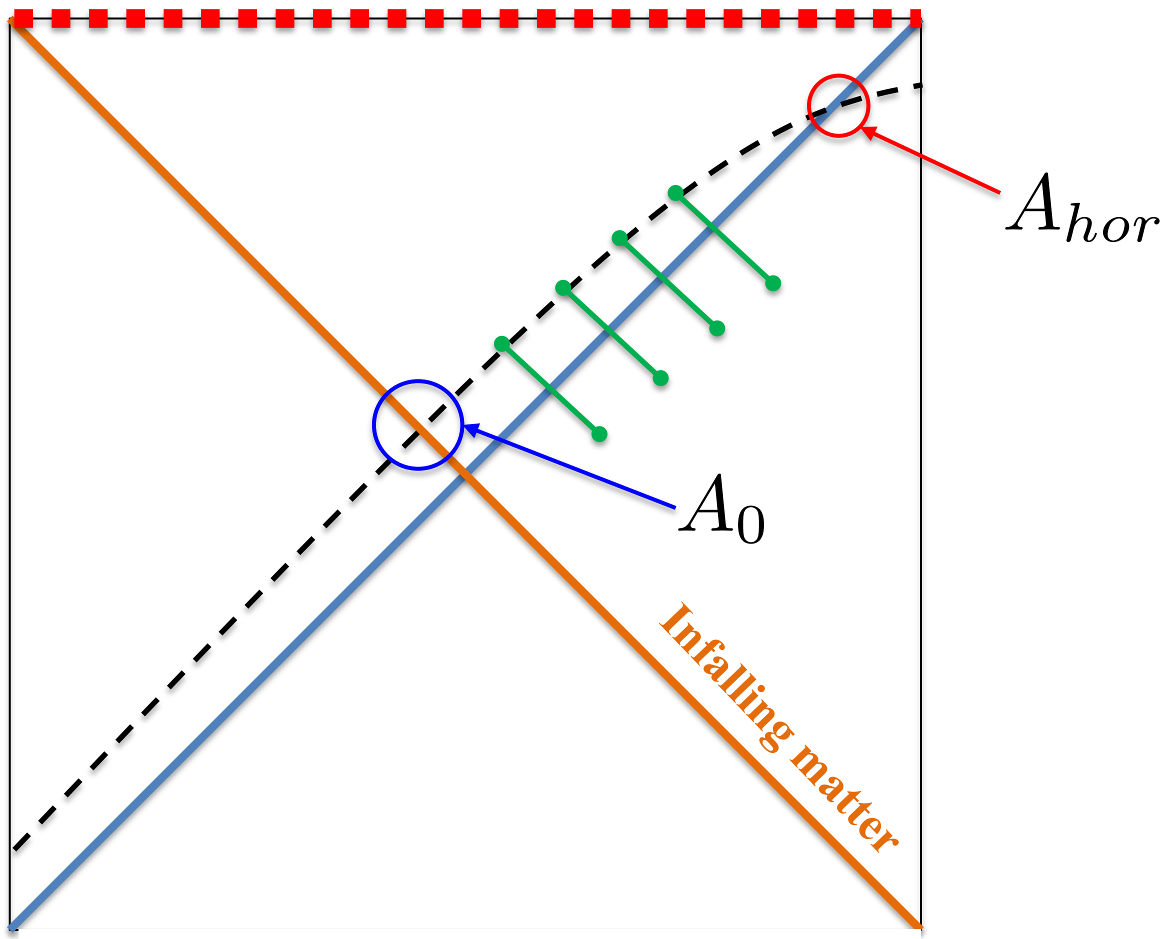

*Minimax*: minimal of all maximal cuts for all the possible slicing.

Largest minimal cut

**The restricted complexity of scrambling tensor network is**

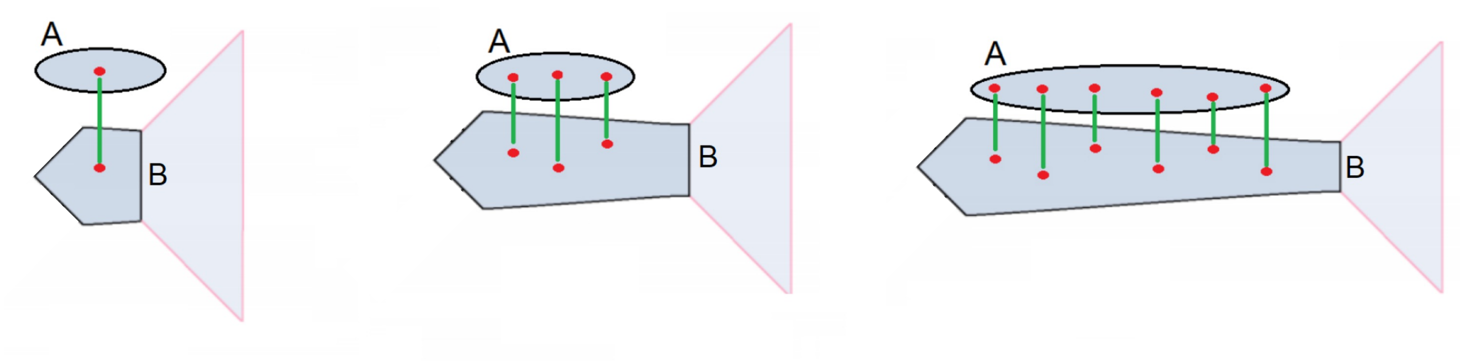
$$\mathcal{C}_R \propto C_{TN} \cdot \exp\left[\frac{1}{2}\Big(N_{\max} - N_{\min\#2}\Big)\right]$$

# The python's lunch in evaporating black hole



# The python's lunch in evaporating black hole

Naïve picture of evaporation process

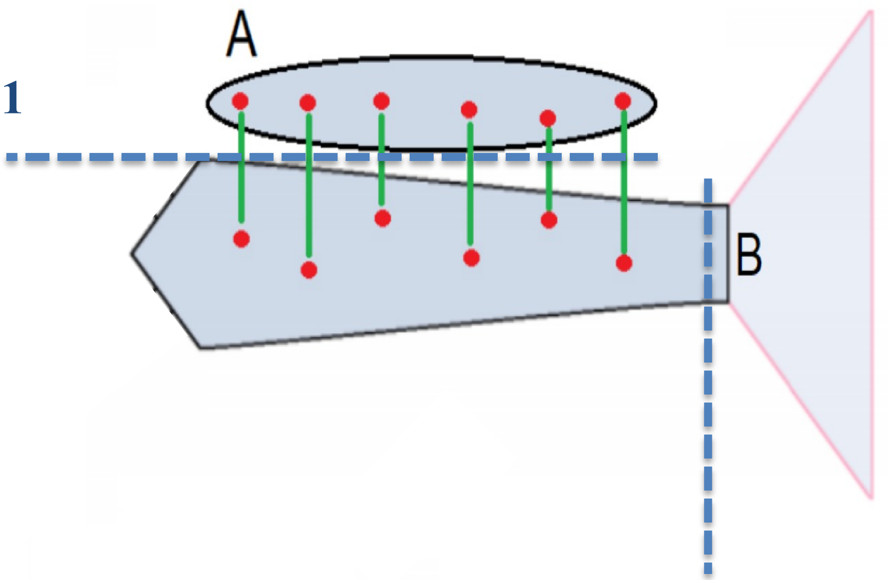



A is the radiation modes. B is the remaining black hole, some nice Cauchy slice going into the horizon.

# The python's lunch in evaporating black hole

Minimal Cut #1

$$S_{rad}$$




**Page time**

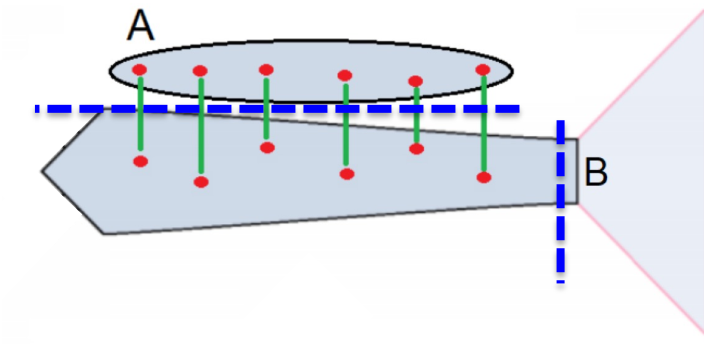
$$S_{rad} = \frac{A_{hor}}{4\hbar G}$$

Minimal Cut #2

$$\frac{A_{hor}}{4\hbar G}$$

**What about the maximal cut?**

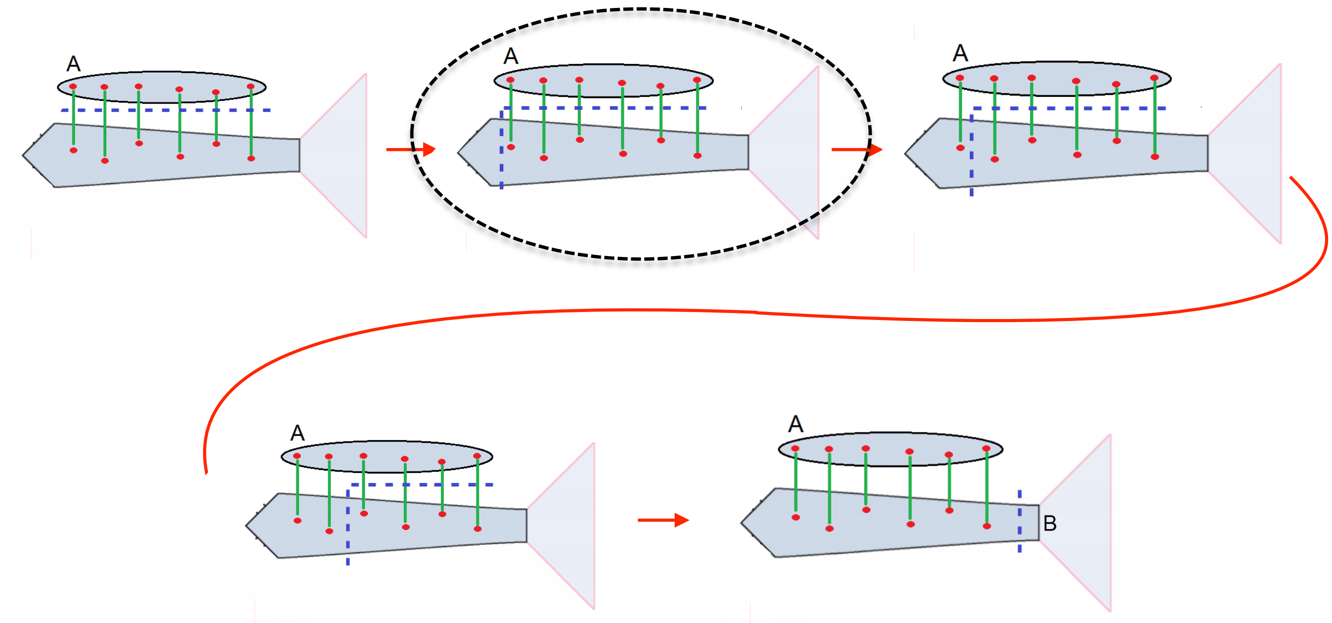
# Covariant definition of python's lunch




**Both minimal cuts are quantum extremal surfaces (extremize the generalized entropy).**
[Engelhardt, Wall 2014]

***Maximin prescription:*** **find the surfaces with smallest and second smallest generalized entropy then maximize over choice of Cauchy surfaces.**
[Wall 2012, AEPU 2019 ]

# Python's lunch search for maximal cut

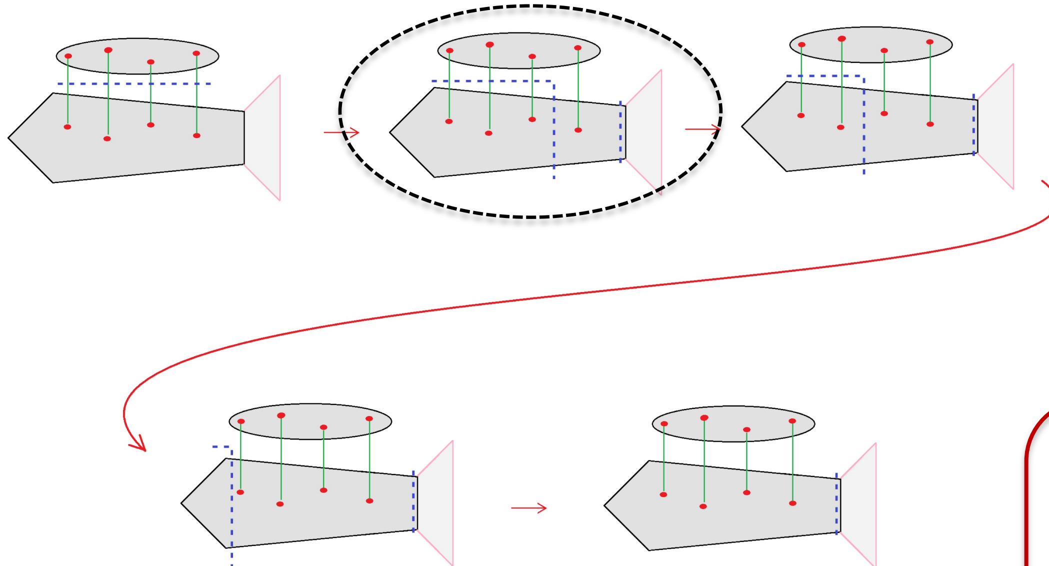



**Before half time, we will be to forward slicing. The maximal generalized entropy.**

$$S_{max}^{(gen)} = S_{rad} + \frac{A_0}{4\hbar G}$$

***Minimax*****: *find* minimal of maximums of all slices.**

# Python's lunch search for maximal cut



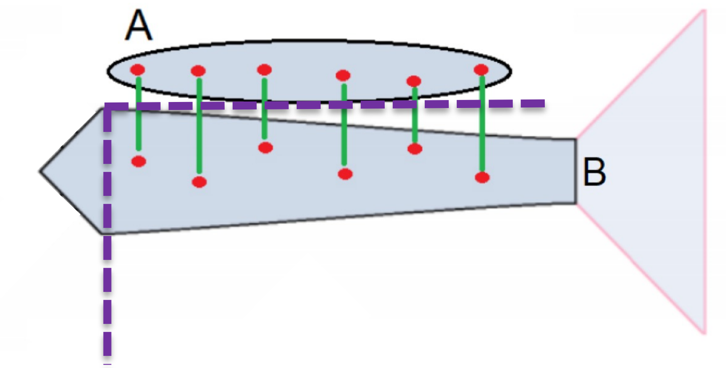
**Half time**

$$A_{hor} = \frac{A_0}{2}$$

**After half time, we will perform reverse slicing.**

$$S^{(gen)}_{max} = S_{rad} + 2\frac{A_{hor}}{4\hbar G}$$

# Covariant definition of python's lunch




***Minimax***: maximal cut for each Cauchy slice find the minimum of the all maximal cuts for all possible slicing methods. Analogous to the tensor network story.

***Maximinimax***: maximize again over all Cauchy surfaces, giving non-minimal quantum extremal surface.

We find this cuts explicitly for **JT gravity plus non-interacting fermions** and verify the picture from the nice Cauchy slice.

# Conjecture: restricted complexity for evaporating black hole

**The restricted complexity of evaporating black hole is**

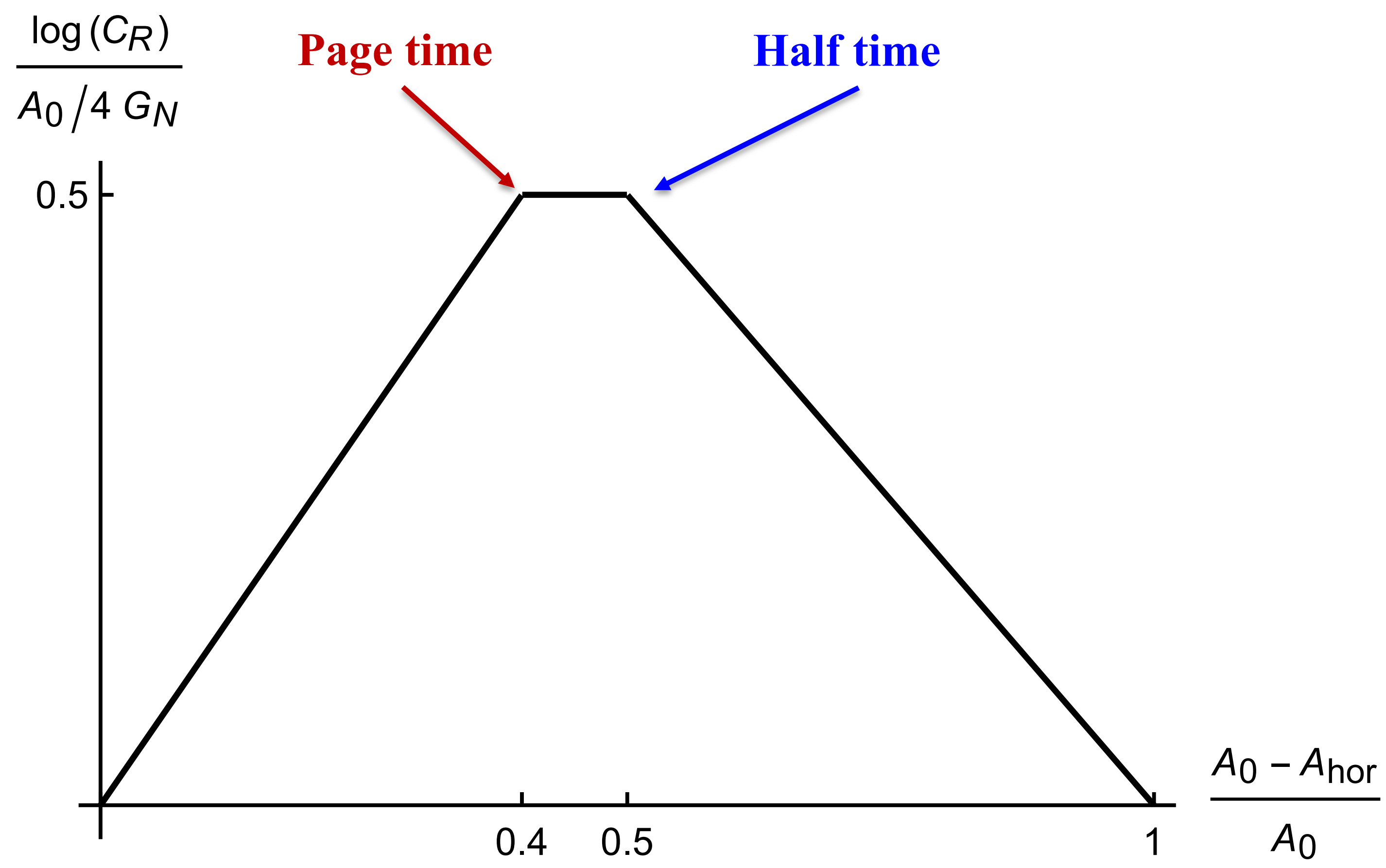
$$C_R \propto C_{TN} \cdot \exp\left[\frac{1}{2}\left(S_{max}^{(gen)} - S_{min}^{(gen)}\right)\right]$$

**Volume/Action (unrestricted complexity)**

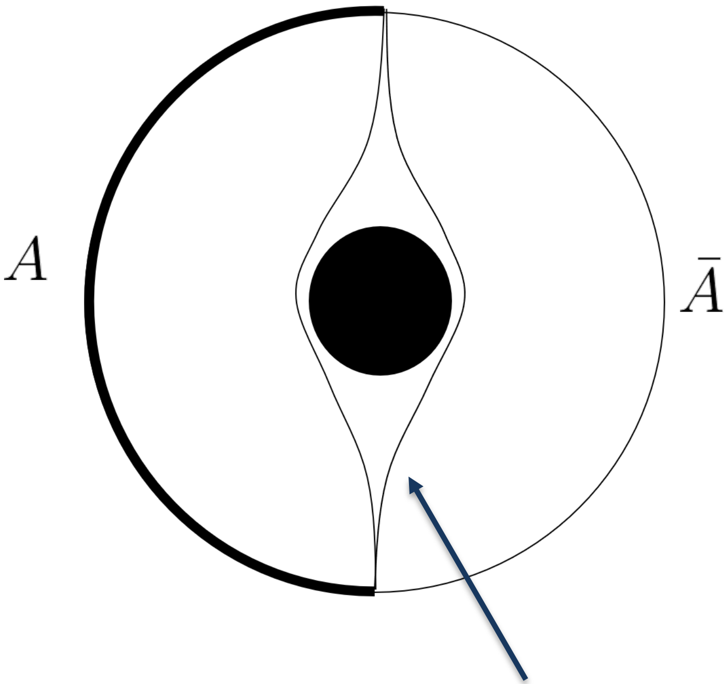
**Maximinimax prescription**

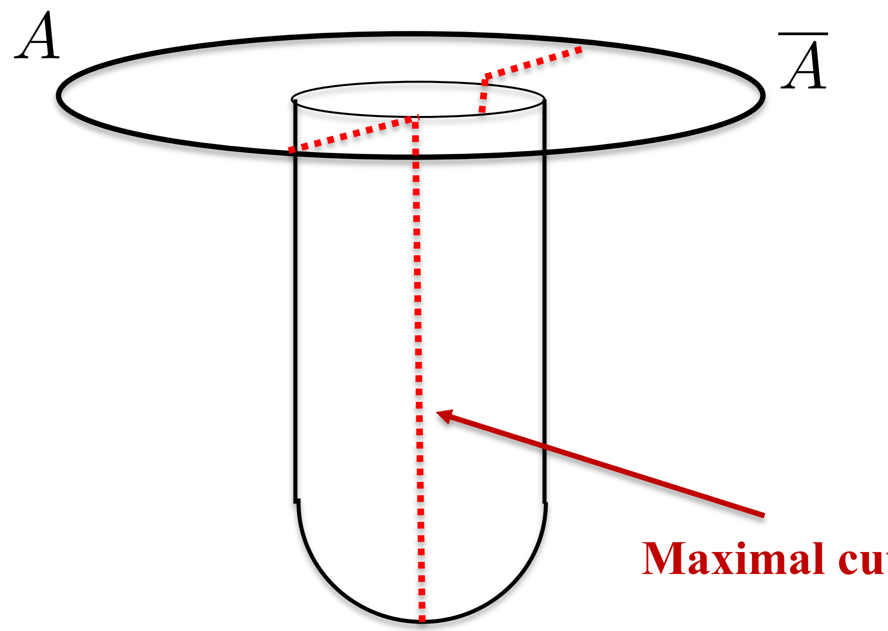
**Maximin prescription**

# Restricted complexity for evaporating black hole

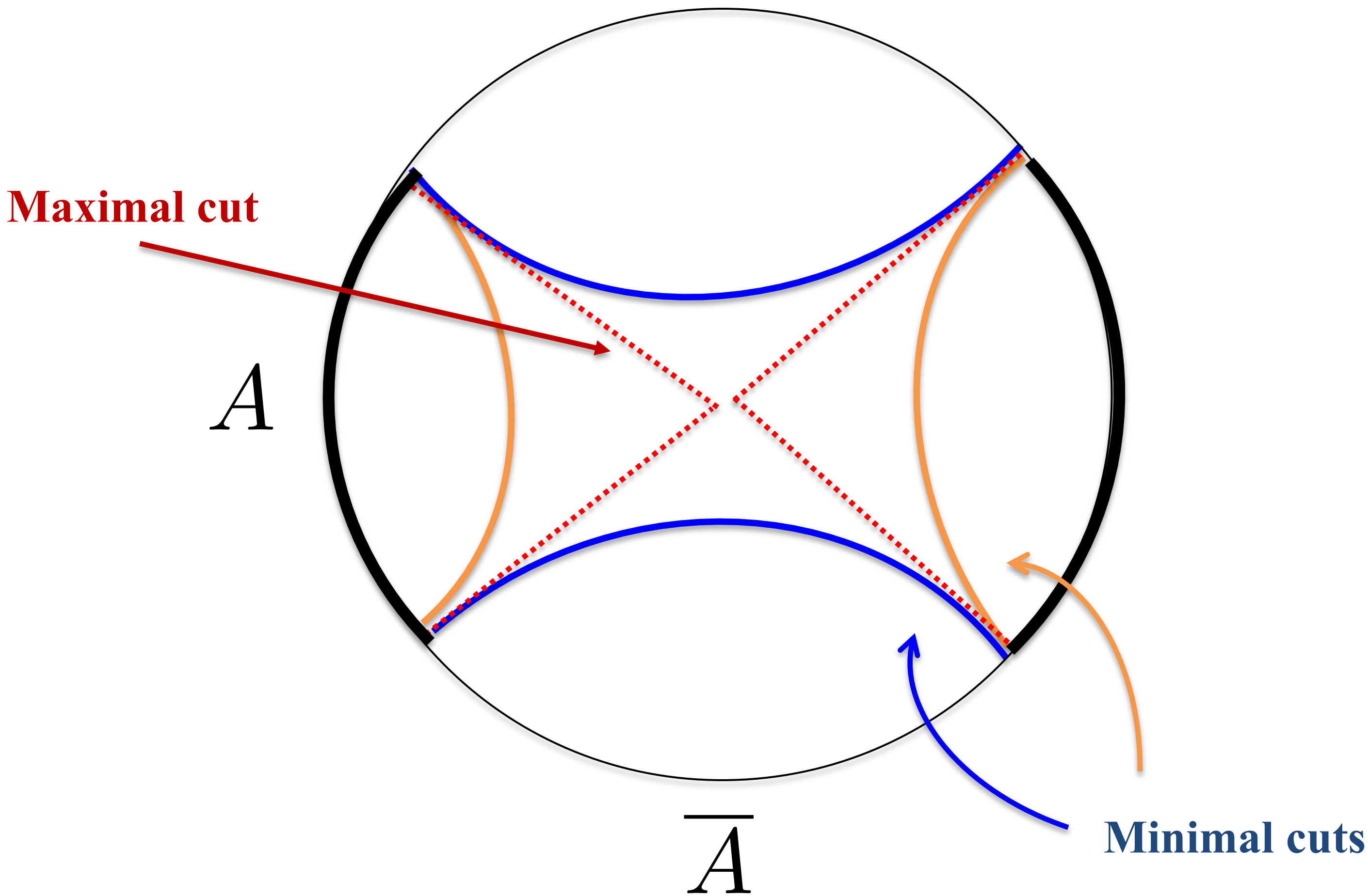


# Python's lunch in pure state black hole



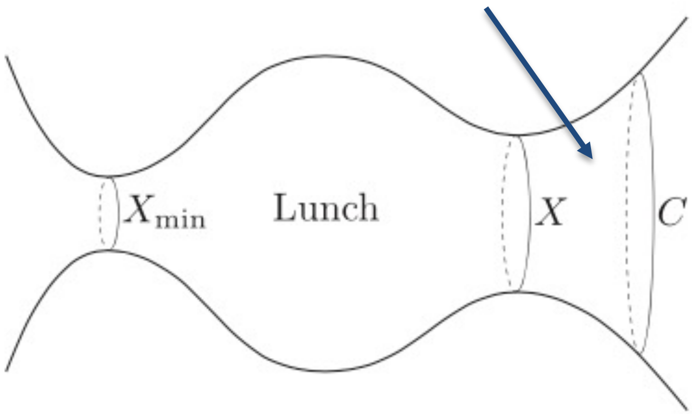



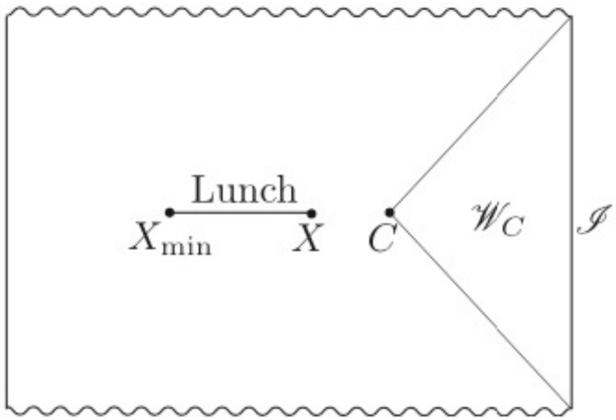
# Python's lunch without black holes – empty AdS



# Converse of Python's lunch conjecture

**Easy to reconstruct**




- HKLL construction
- Causal bulk propagation of perturbed boundary condition on Lorenzian timefolds

[Engelhardt, Penington, Shahbazi-Moghaddam 2021]

# Final remarks

**Summary:** The restricted complexity of python's lunch is

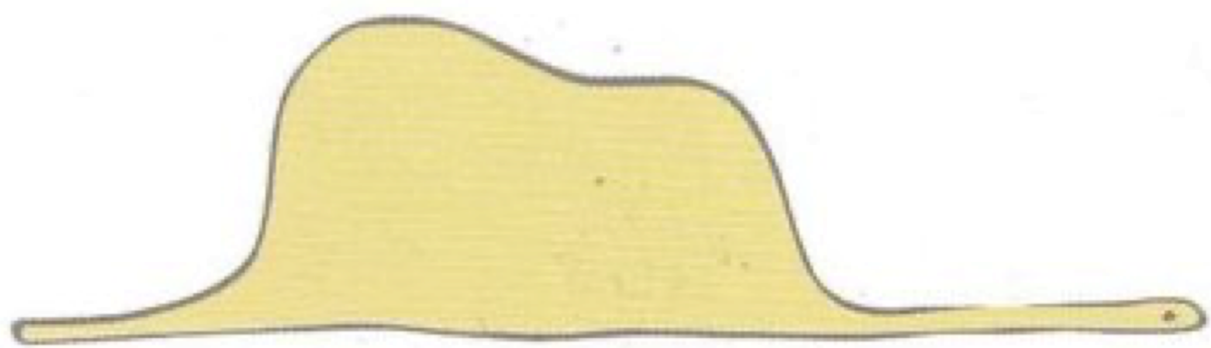
$$C_R \propto C_{TN} \cdot \exp\left[\frac{1}{2}\left(S_{max}^{(gen)} - S_{min}^{(gen)}\right)\right]$$

**Future directions**

- Test this conjecture in quantum field theories, perhaps with alternative definition of complexity
- Study other examples when python's lunches and non-minimal quantum extremal surfaces appear; pure state black holes and empty AdS.
  - What does this imply about reconstruction of operators in the python's lunch?

# The End

**The python’s lunch**



# Appendix

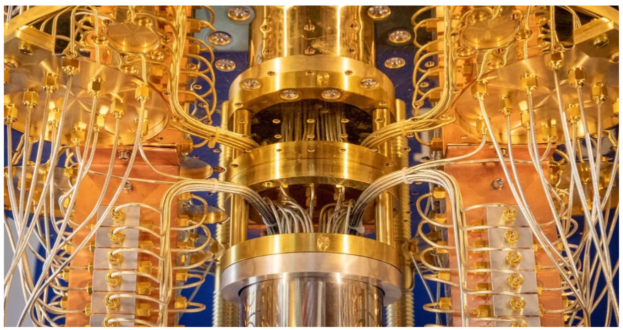
# Part Three

**Quantum gravity in the lab: teleportation by size and traversable wormholes**

**Based on arXiv: 1911.06314 and 2102.01064**

# Simulating quantum gravity via holography

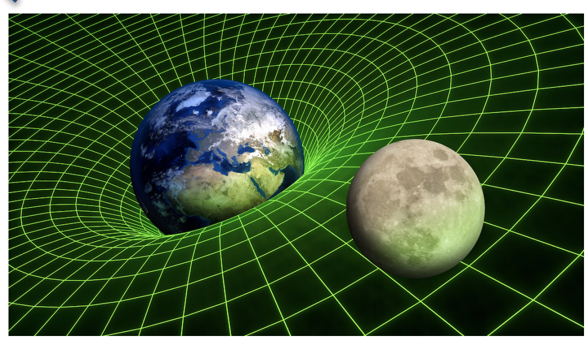
**Quantum Devices**



**Classical Supercomputers**

**Holography (AdS/CFT)**

**Quantum Gravity**



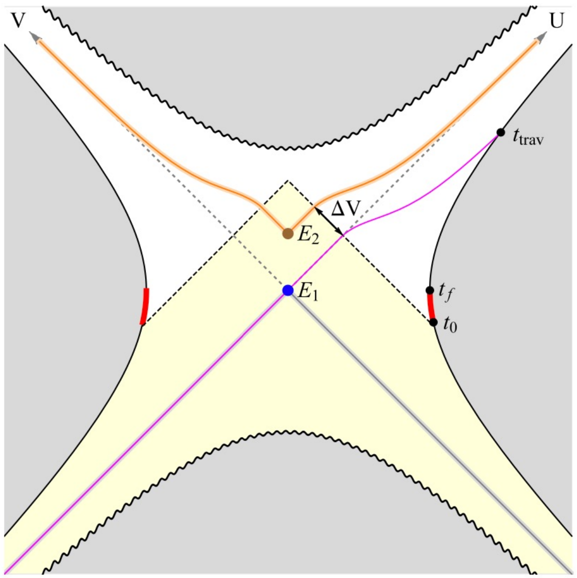
# Traversable wormholes in AdS/CFT

P. Gao, D. L. Jafferis, A. Wall

*"Traversable Wormholes via a Double Trace Deformation"; arXiv: 1608.05687*

J. Maldacena, D. Stanford,

*"Diving into Traversable Wormholes"; arXiv: 1704.05333*

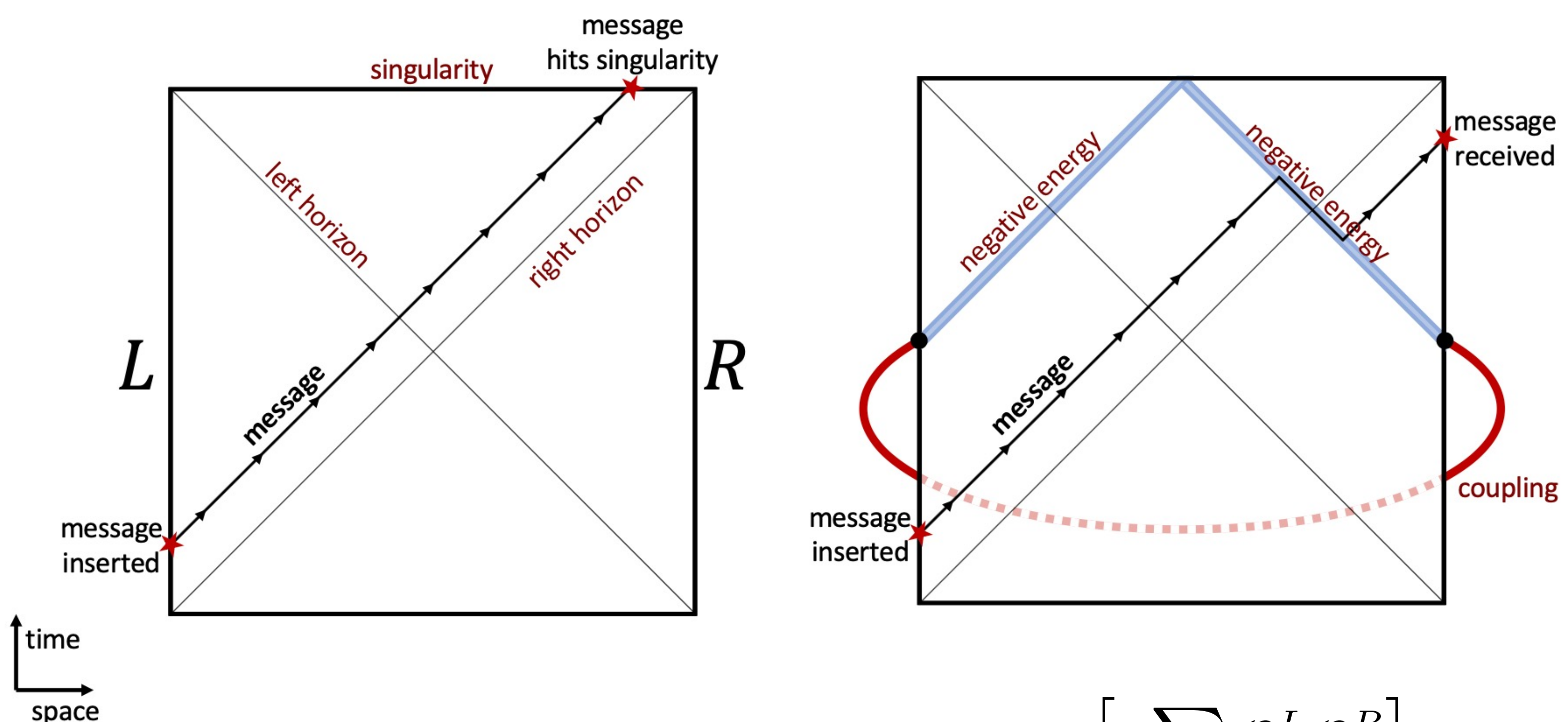



**Couple left and right CFT's**

$$\exp\left[g\sum_i \mathcal{O}_i^L \mathcal{O}_i^R\right]$$

**Sends a negative energy particles in black hole in AdS that makes the wormhole traversable.**

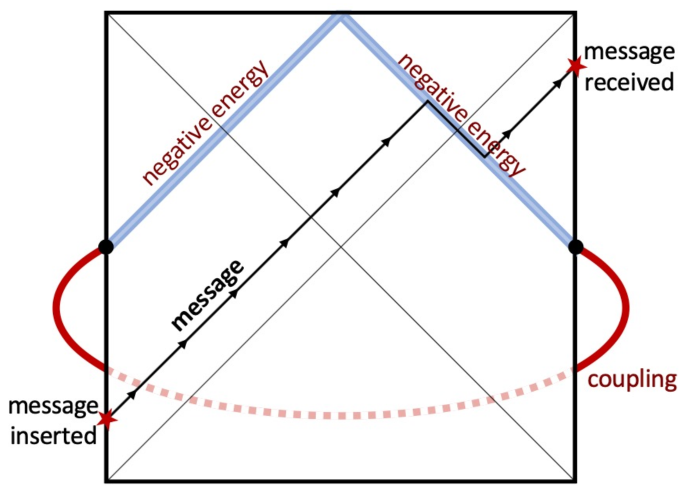
# Is traveling through the wormhole a new kind of teleportation protocol?



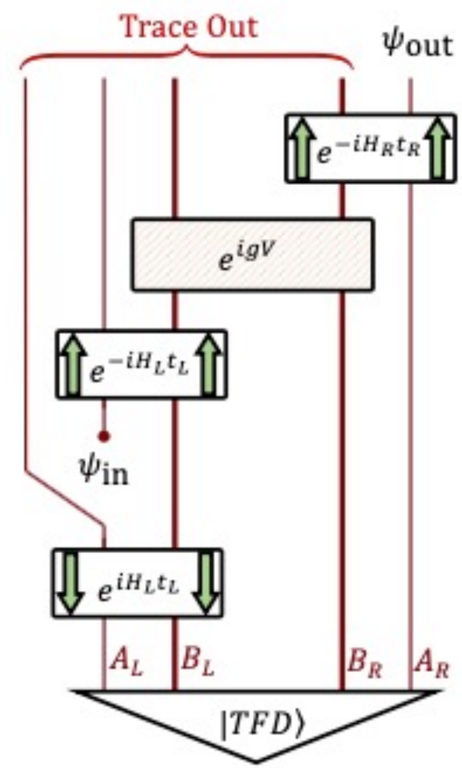

**Couple:** $\exp\left[g\sum_i \mathcal{O}_i^L \mathcal{O}_i^R\right]$

# Understanding the flow of quantum information flow on the boundary

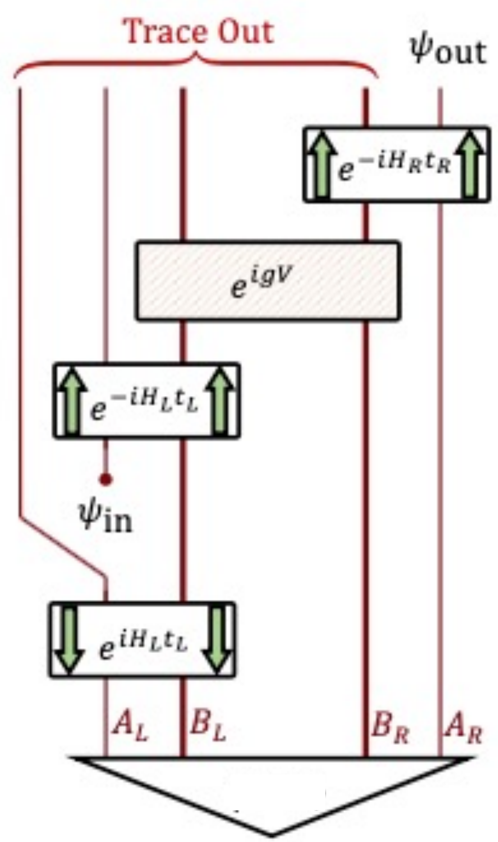
**AdS/CFT set up**




**Boundary interpretation?**



# Understanding the flow of quantum information flow on the boundary




$|TFD\rangle_\beta$

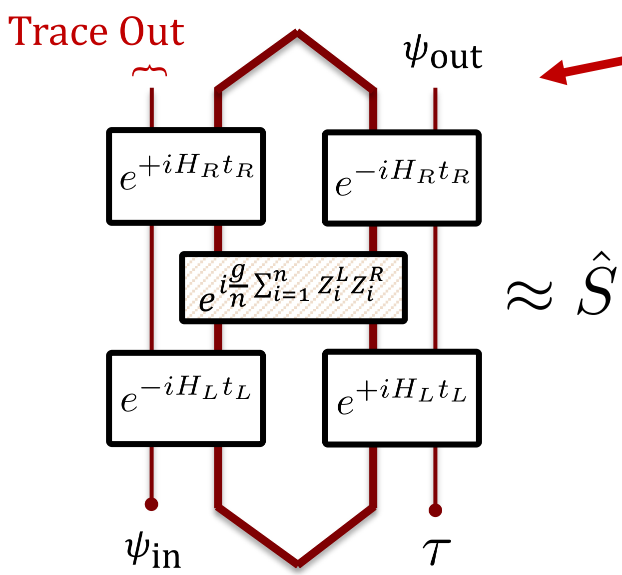
$H_L, H_R$ **:left and right Hamiltonians**

**Couples left-right**

$$V = \sum_i \mathcal{O}_i^L \mathcal{O}_i^R$$

$$|TFD\rangle_\beta = \frac{1}{\sqrt{\mathrm{Tr}\ e^{-\beta H}}} \sum_a e^{-\beta E_a/2} |E_a\rangle |E_a\rangle$$

# Teleportation by size

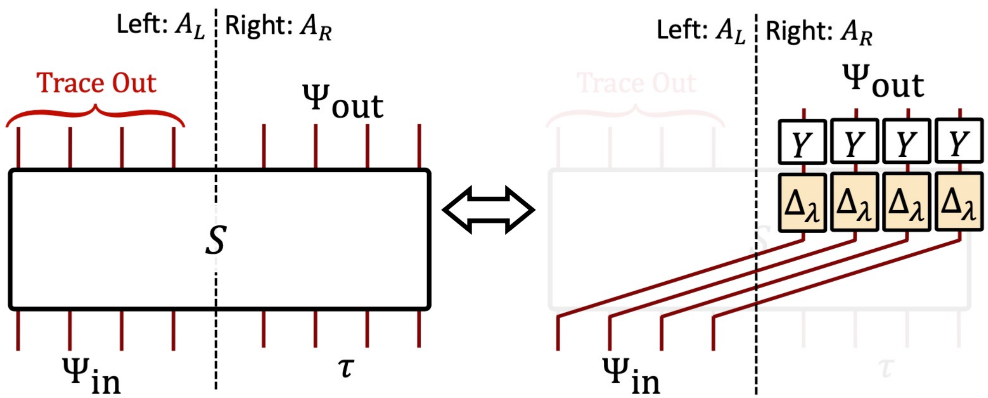



**Simple transformation of the initial circuit**

**Approximately implements size operator S:** random matrix, chaotic spin chains, SYK model

$$\boxed{\hat{S}|P\rangle = e^{ig|P|}|P\rangle}$$

# Teleportation by size



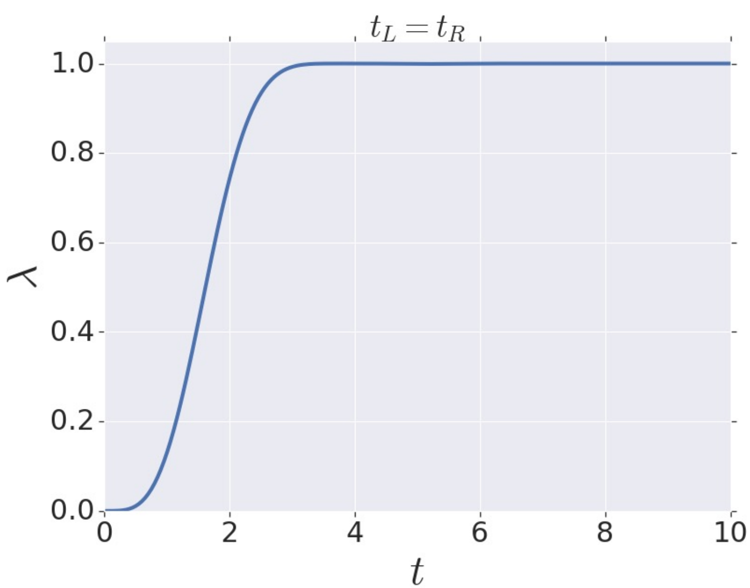

$$\hat{S}|P\rangle = e^{ig|P|}|P\rangle \quad \text{, where} \quad |P\rangle = P|\phi^+_{Bell}\rangle^{\otimes m}$$

$$IIXXIIXYIIZIZ$$ **Pauli strings**

|P| is the **size of the Pauli operator** (number of non-identity elements)

# Regime #1: teleportation of a single qubit

**1. Teleports a single qubit with perfect fidelity.**

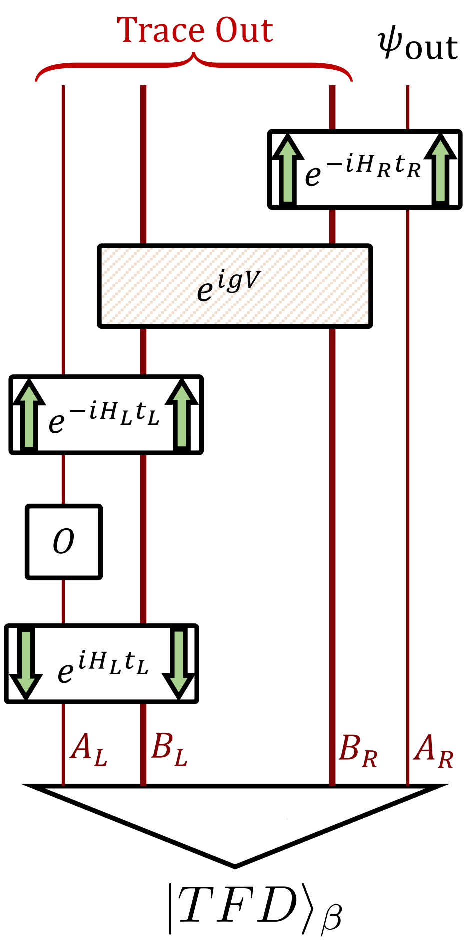



**2. Works for all times after scrambling time.**

**3. Works the best at infinite temperature.**

$$|TFD\rangle_{\beta=0} = |\phi^+_{Bell}\rangle^{\otimes n}$$

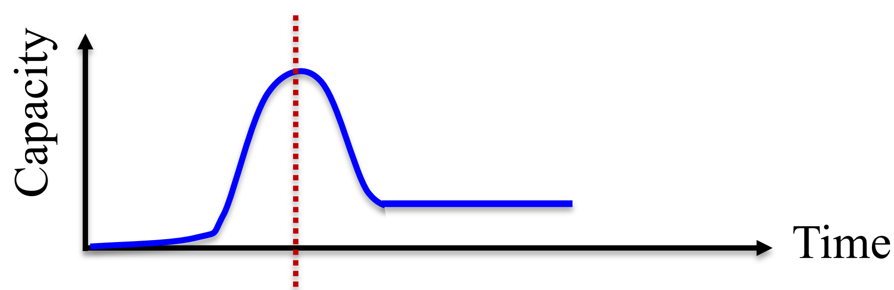
# Regime #2: more qubits and low temperatures



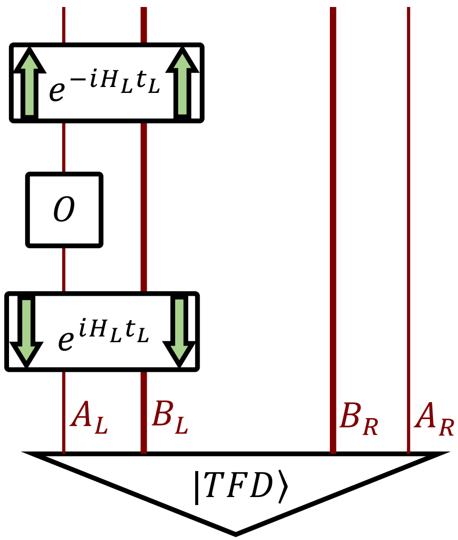

**At low temperature a new phenomena appears**

**We can teleport more then a single qubit**

**This works for Hamiltonians with holographic duals: example is SYK model**



# Regime #2: size winding explained




$|TFD\rangle_\beta$

**Operator growth in thermal ensemble**

$$\mathcal{O}(t)\rho_\beta^{1/2} = e^{-iHt}\mathcal{O}e^{+iH(t+\frac{\beta}{2})} = \sum_P c_P(t)P$$

**complex**

**Size-winding phenomena**

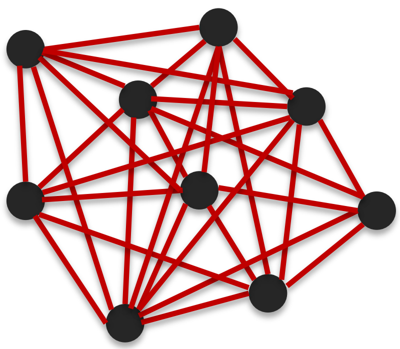
$$q(l) = \sum_{|P|=l} c_P^2 = e^{i\theta}\sum_{|P|=l}|c_P|^2$$

**The phase of the size-distribution winds near scrambling time:**

$$\boxed{\theta \sim l \times (const)}$$

# Regime #2: size winding in SYK model

**Size-winding is hard to illustrate from the boundary analytically.**



**Sachdev-Ye-Kitaev**

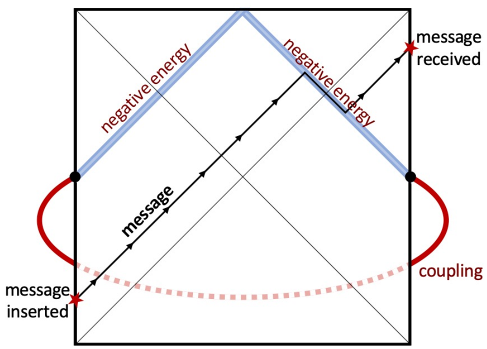
$$H_{SYK} = \sum_{i,j,k,l} J_{ijkl}\chi_i\chi_j\chi_k\chi_l$$

**We verify the results noticed earlier in JT gravity**

$$\boxed{\text{Moment } = \text{Operator Size}}$$

**Bulk AdS** **Boundary CFT**

# Regime #2: size winding and teleportation




**Left operator action**

$$\mathcal{O}_L(-t_*)|TFD\rangle_\beta = \sum_P e^{+i\alpha|P|/n} r_P|P\rangle$$

**Plus the coupling**

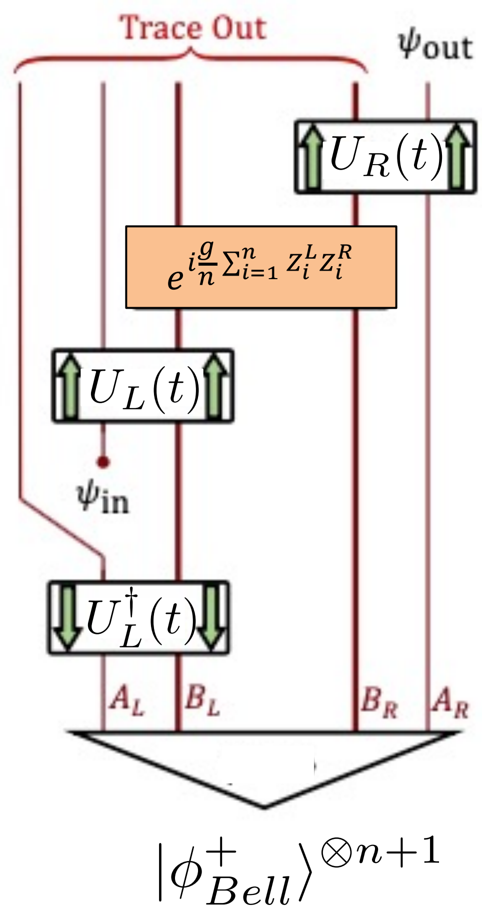
$$e^{igV}|P\rangle \approx e^{\frac{i4g|P|}{3n}}|P\rangle$$

**Will equal to an operator acting on the right**

$$\mathcal{O}_R(+t_*)|TFD\rangle_\beta = \sum_P e^{-i\alpha|P|/n} r_P|P\rangle$$

[Closely related work by Schuster et.al arXiv:2102.00010]

# Experimental realizations




**We discuss several experimental realizations that are within reach:**

Superconducting qubits,
Rydberg atoms, Trapped ions

**Floquet version of Rydberg dynamics**

$$U_R(t) = U_L(t) = U^t$$

**where each time step is** $U = U_K U_L$

$$U_K = \exp\left[ib\sum_i X_i\right]$$

$$U_L = \exp\left[i\sum_i h_i Z_i + iJ\sum_i Z_i Z_{i+1}\right]$$

# What can we learn about quantum gravity (holography) using the tools of quantum information and computation?

- ❖ Complexity =Volume conjecture for evaporating black hole and **the python's lunch** [arXiv:1912.00228]

$$C_R \propto C_{TN} \cdot \exp\left[\frac{1}{2}\left(S_{max}^{(gen)} - S_{min}^{(gen)}\right)\right]$$

- ❖ Holographic complexity in **JT gravity** [arXiv:1810.08741]
- ❖ Onset of chaos in **SFF** from random quantum circuits [arXiv:1803.08050]

**Future research:**

- ➢ Find other examples of holography where python's lunch appears
- ➢ Test this conjecture in quantum field theories, perhaps with alternative definition of complexity

# Can we study deep questions about quantum gravity in the near term quantum devices? (quantum gravity in the lab)

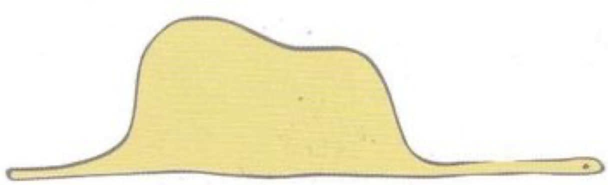
- ❖ **Teleportation by size** protocol inspired by traversable wormholes
- ❖ The **size winding** phenomenon and connection to semi-classical gravity duals [arXiv:1911.06314 and 2102.01064]
- ❖ Simulating **matrix quantum mechanics** on a quantum computer (BFSS/BMN holographic dual to string theory) [arXiv: 2011.06573]

**Future research:**

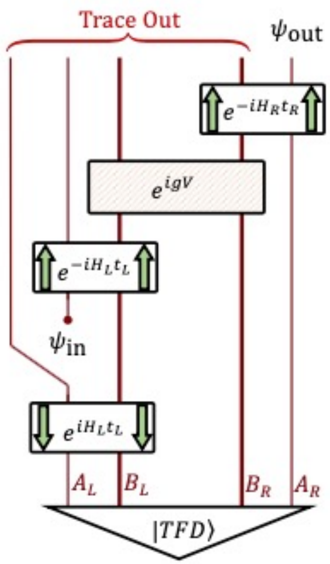
- ➢ What is the link between maximal chaos (in OTOC) and size winding?
- ➢ Teleportation protocol for GHZ-like entangled state
- ➢ Construct new protocols and observables that have quantum gravity interpretation and can be measured in near term experiments

# The End

**The python's lunch**



**Quantum gravity in the lab**

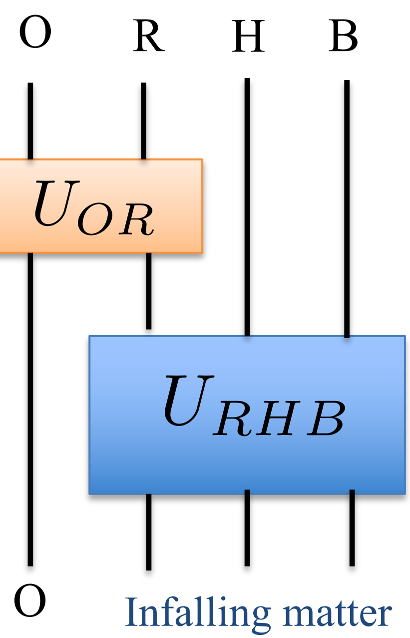


# Appendix

# Hawking radiation is pseudorandom (2019)

I. Kim, E. Tang, J. Preskill,

*" The ghost in the radiation: Robust encodings of black hole interior";  arXiv:2003.05451*

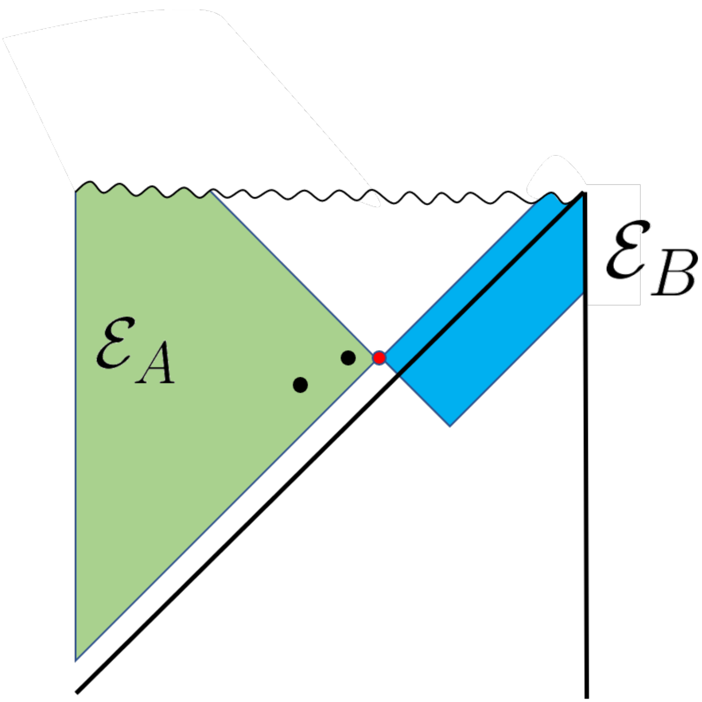


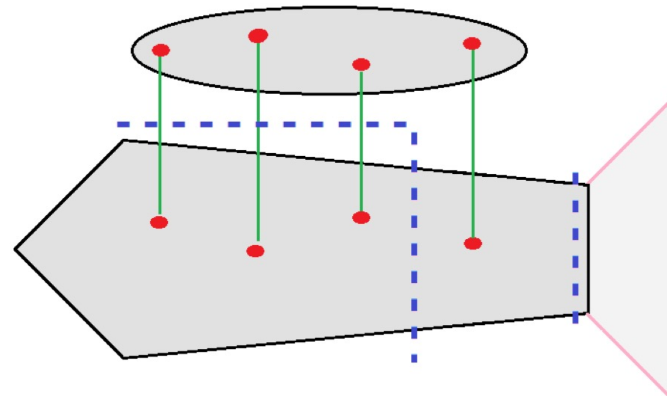

- RB radiation state is pseudorandom
- Computationally bounded observer O cannot destruct encoding of A in RB system.
- Implies that decoding Hawking radiation required exponential complexity

$$\text{complexity} \sim e^{S}$$

[Kim, Tang, Preskill et. al 2020]

# Covariant python's lunch maximal cut (reverse sweep)



***Maximinimax prescription:***

$$S_{max}^{(gen)} = S_{rad} + 2\frac{A_{hor}}{4\hbar G}$$

# Post-selecting a qutuit

$$U|s\rangle|1\rangle = \frac{|\alpha\rangle|1\rangle + |\beta\rangle|2\rangle + |\gamma\rangle|3\rangle + |\delta\rangle|4\rangle}{2}$$

$$V \equiv 1 - 2|\tilde{\alpha}\rangle\langle\tilde{\alpha}| = U^\dagger\Big(\mathbb{1} \otimes (\mathbb{1} - 2|1\rangle\langle 1|)\Big)U.$$

$$U_s \equiv 2|s\rangle\langle s| \otimes |1\rangle\langle 1| - \mathbb{1}$$

$$|\tilde{\alpha}\rangle \equiv U^\dagger|\alpha\rangle|1\rangle \quad ; \quad |\tilde{\beta}\rangle \equiv U^\dagger|\beta\rangle|2\rangle$$

$$|\tilde{\gamma}\rangle \equiv U^\dagger|\gamma\rangle|3\rangle \quad ; \quad |\tilde{\delta}\rangle \equiv U^\dagger|\delta\rangle|4\rangle$$

$$\begin{aligned} V|s\rangle|1\rangle &= \frac{1}{2}(-|\tilde{\alpha}\rangle + |\tilde{\beta}\rangle + |\tilde{\gamma}\rangle + |\tilde{\delta}\rangle) \\ U_s V|s\rangle|1\rangle &= |\tilde{\alpha}\rangle \\ U\Big[U_s V\Big]|s\rangle|1\rangle &= |\alpha\rangle|1\rangle \end{aligned}$$

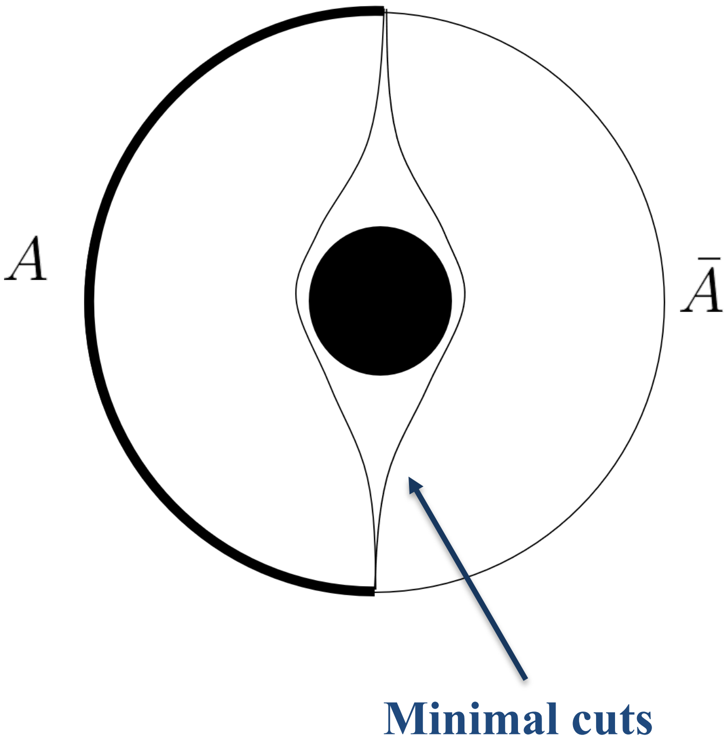
# Post-selecting multiple qubits

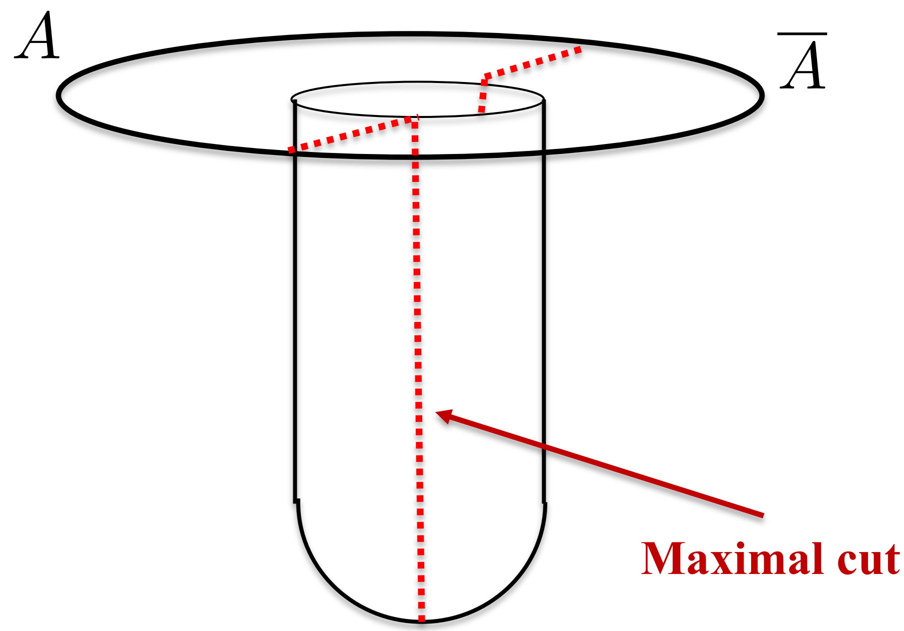
$$U|s\rangle|0\rangle^{\otimes n} = \sin\theta|\alpha\rangle|0\rangle^{\otimes m} + \cos\theta|\beta\rangle$$

$$\begin{aligned} U_s &= 2|s\rangle\langle s| \otimes |0\rangle\langle 0|^{\otimes n} - \mathbb{1} \\ V &= U^\dagger\Big(\mathbb{1} \otimes (\mathbb{1} - 2|0\rangle\langle|^{\otimes m})\Big)U \end{aligned}$$

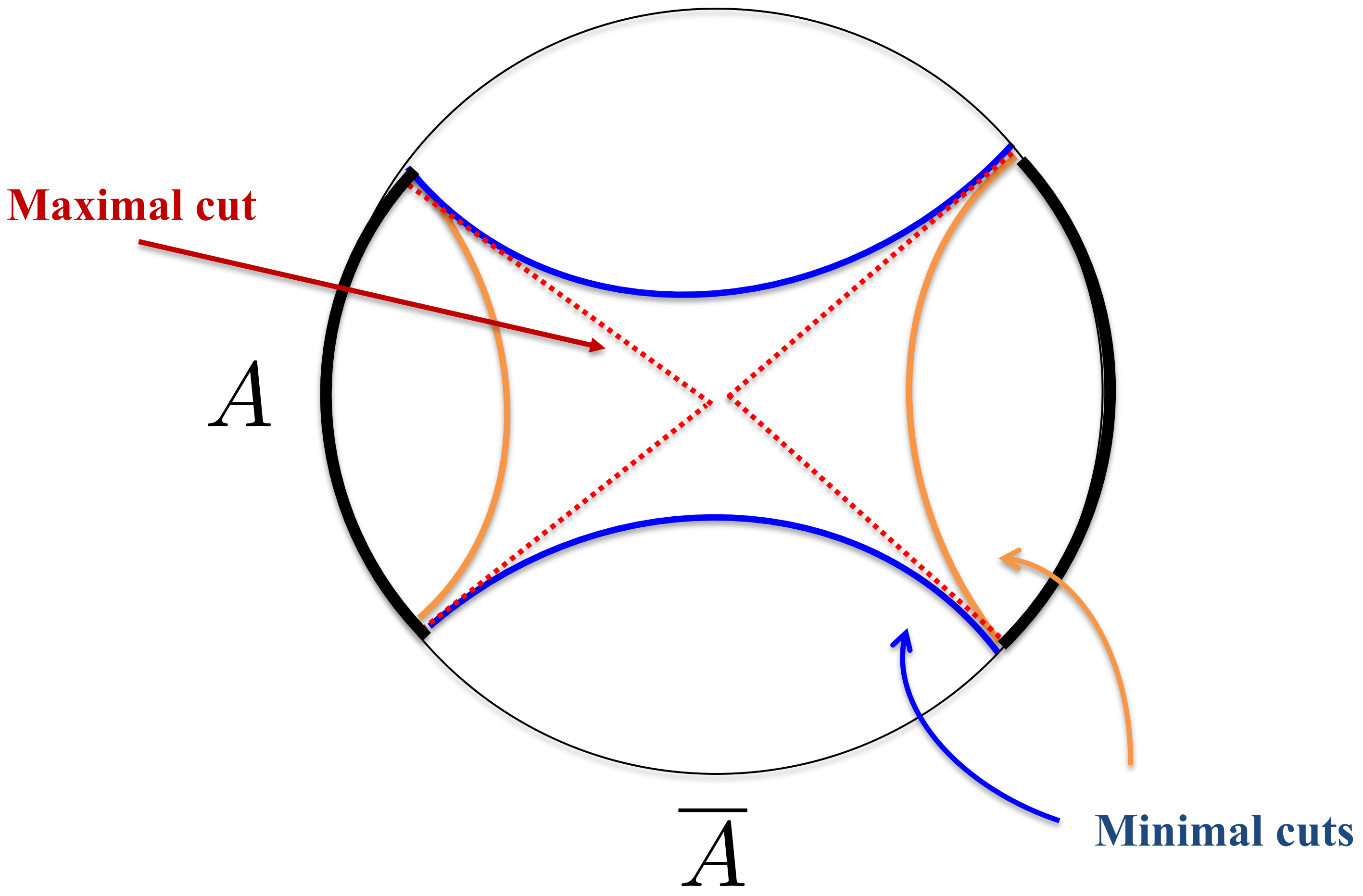
$$U\Big[U_s V\Big]^l|s\rangle|0\rangle^{\otimes n} = \sin[(2l+1)\theta]|\alpha\rangle|0\rangle^{\otimes m} + \cos[(2l+1)\theta]|\beta\rangle$$

# Python's lunch in pure state black hole

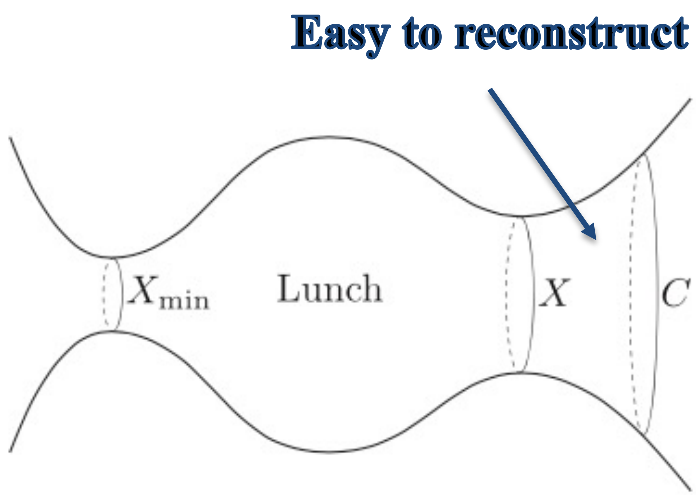


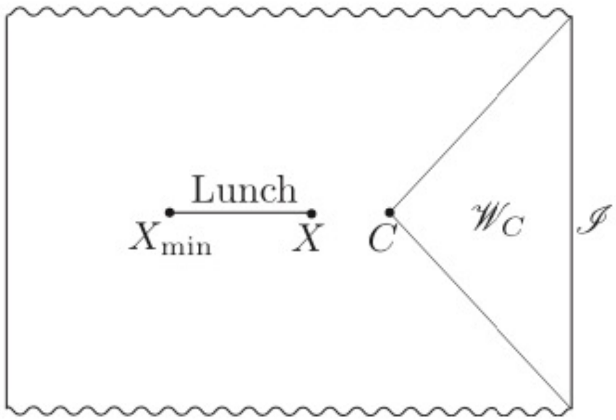



# Python's lunch without black holes – empty AdS



# Converse of Python's lunch conjecture




- HKLL construction
- Causal bulk propagation of perturbed boundary condition on Lorenzian timefolds

[Engelhardt, Penington, Shahbazi-Moghaddam 2021]

# What's the complexity of removing post-selection / final state projection?

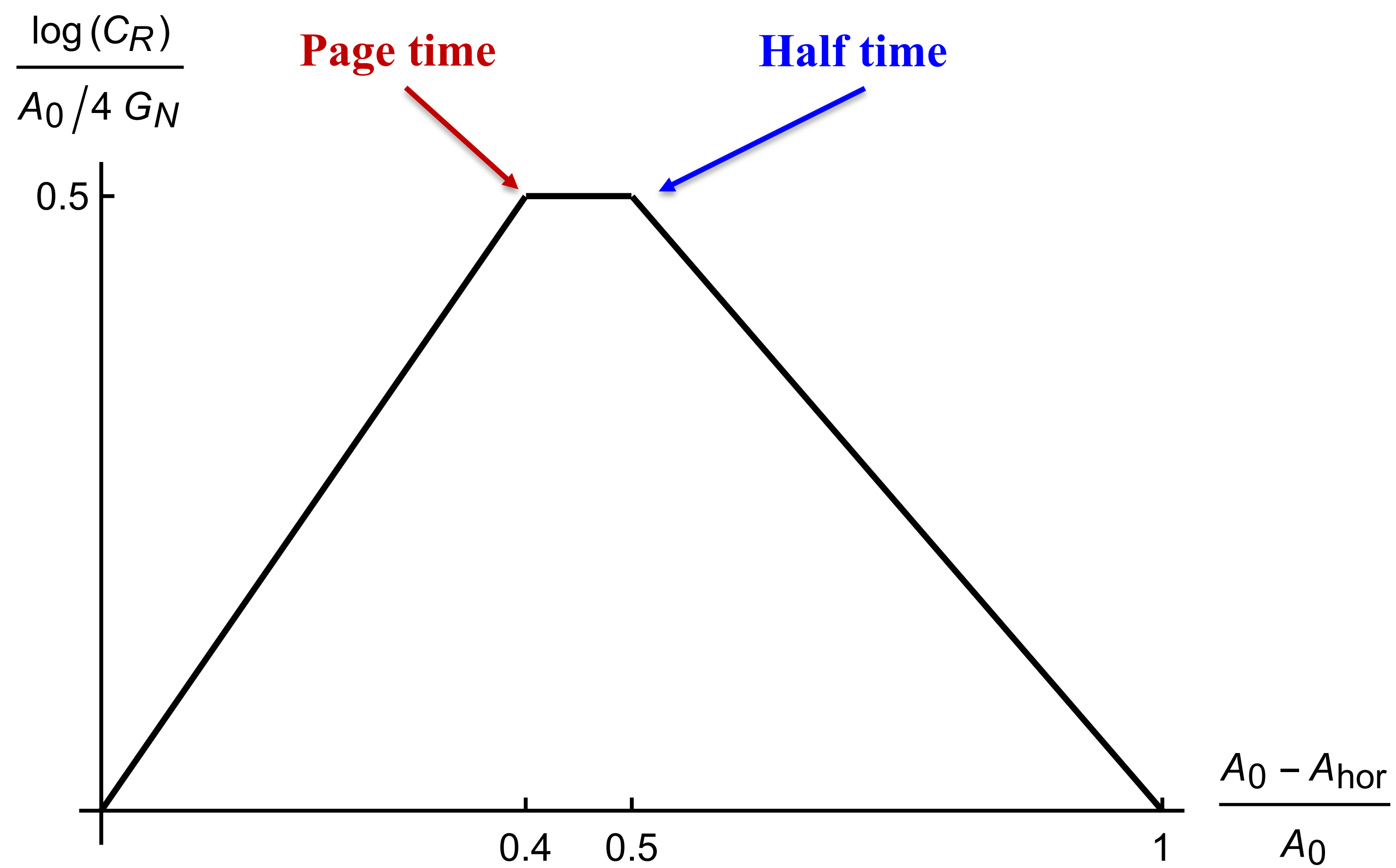
We can measure the qubits and hope to get the right answers.
Probability of the right answer is $1/2^m$ and expected complexity

$$C \propto 2^{m_R} \cdot C_{TN}$$

It is not a fixed unitary and complexity can be improved.

We can do a generalized **Grover-like search.**

# Restricted complexity for evaporating black hole



# When are restricted and unrestricted complexities very different?

**python's lunch**

# Final remarks

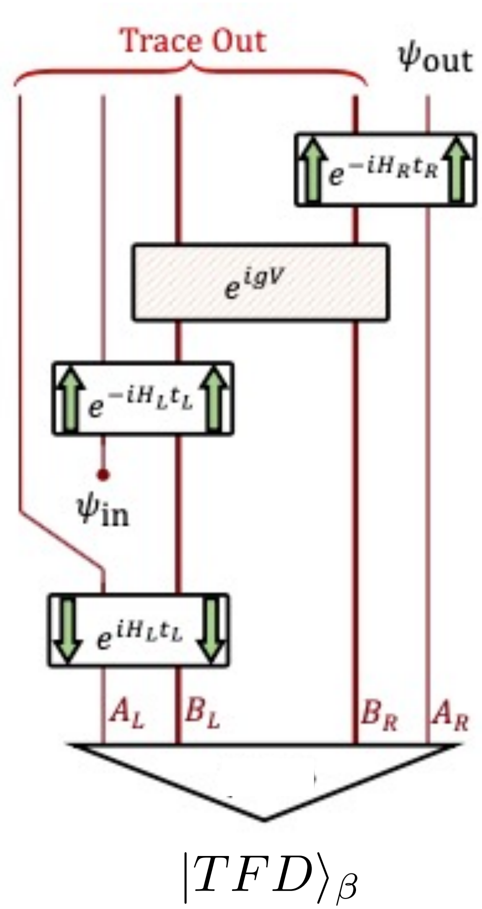
**Summary:** The restricted complexity of python's lunch is

$$C_R \propto C_{TN} \cdot \exp\left[\frac{1}{2}\left(S_{max}^{(gen)} - S_{min}^{(gen)}\right)\right]$$

**Future directions**

- Prove this formula beyond tensor network formalism, perhaps new definition of complexity is needed.
- Study other examples when python's lunches and non-minimal quantum extremal surfaces appear; pure state black holes and empty AdS.
  - What does this imply about reconstruction of operators in the python's lunch?
  - Relationship of python's lunch to quantum extended Church-Turing thesis

# Some Interesting Questions



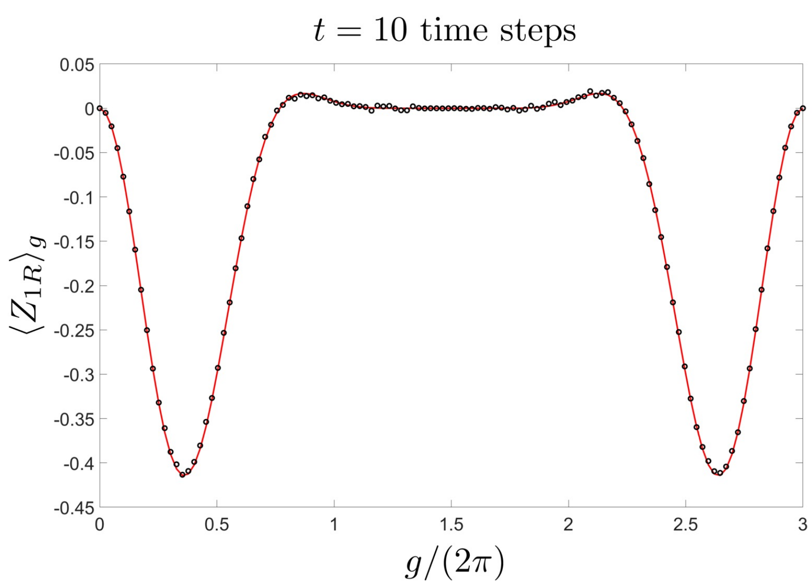

1. **What are the Hamiltonians that can teleport quantum information?**

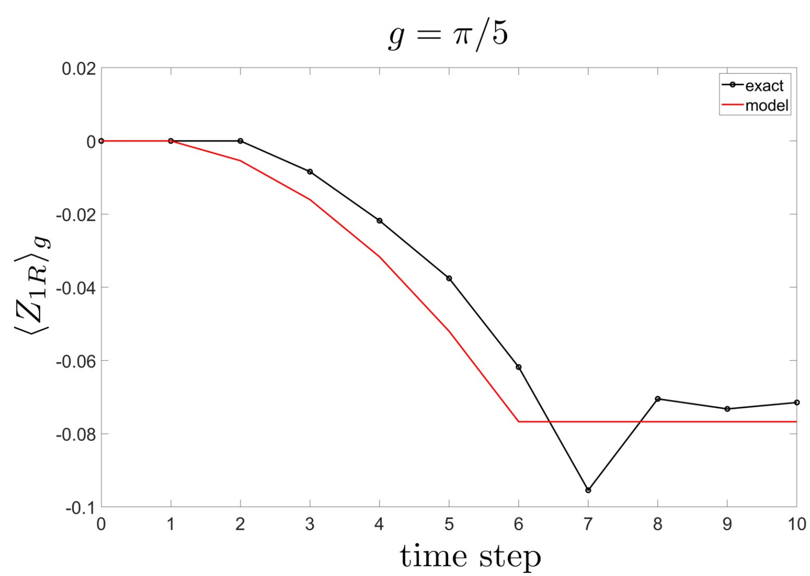
2. **Does the teleportation work at different temperatures?**

3. **How does the teleportation depend on the details of the coupling?**

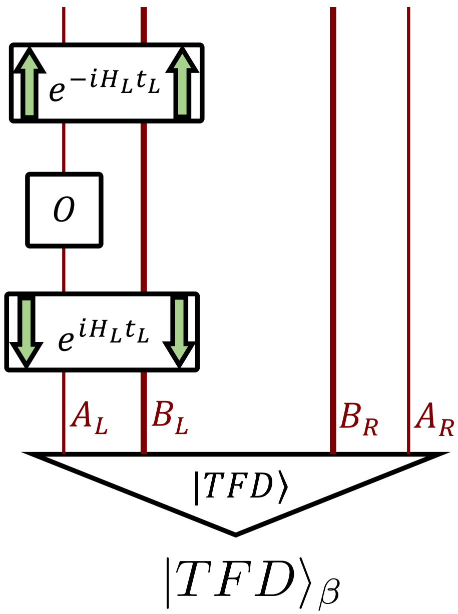
# Regime #1: numerical study of the experimental proposal

**Numerical evidence for Floquet version of Rydberg dynamics for N=7 qubits.**



# Regime #2: size winding explained




**Operator growth**

$$\mathcal{O}(t) = e^{-iHt}\mathcal{O}e^{+iHt} = \sum_P c_P(t) P$$

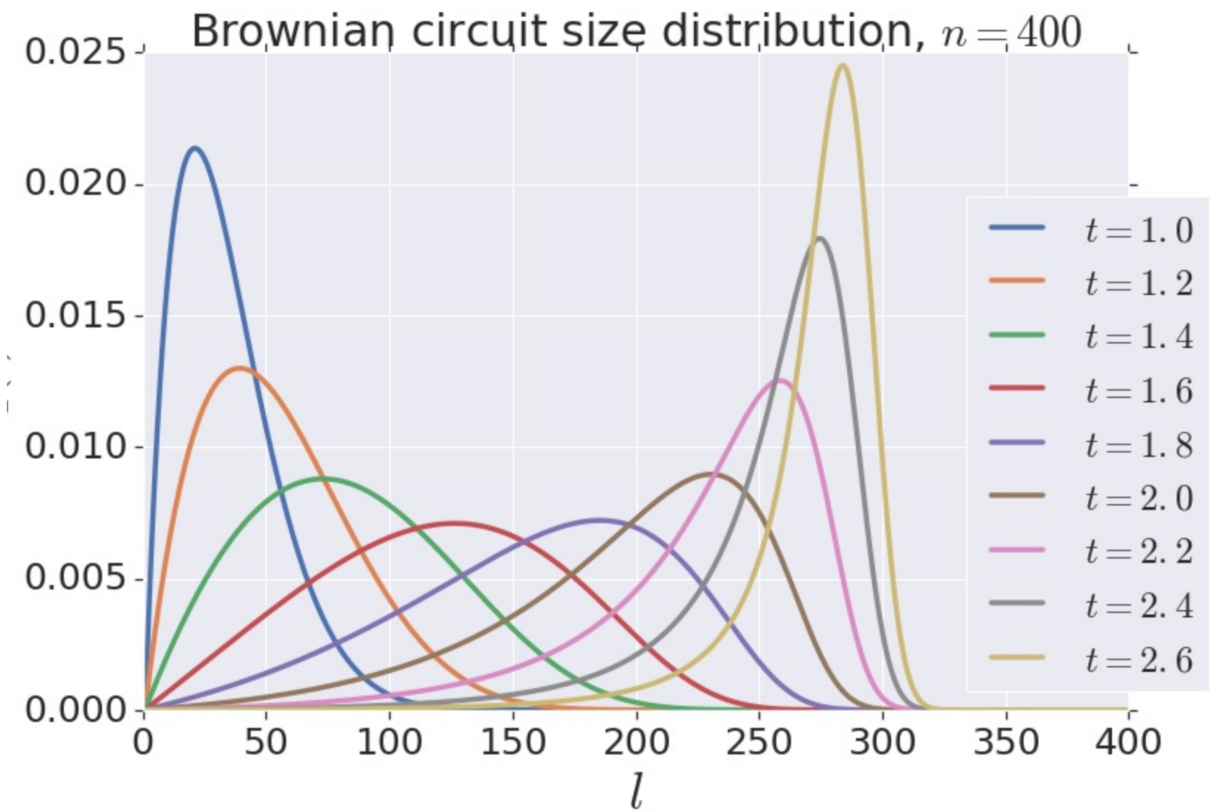
**real**

**Operator size-distribution**

$$p(l) = \sum_{|P|=l} |c_P|^2$$

**For Hermitian operator and finite temperature coefficients are real.**

# Regime #2: Operator Size Distribution



# Regime #2: size winding in SYK model

**Size-winding is hard to illustrate from the boundary analytically.**

**Sachdev-Ye-Kitaev:** $H_{SYK} = \sum_{i,j,k,l} J_{ijkl}\chi_i\chi_j\chi_k\chi_l$

**Majorana fermions**

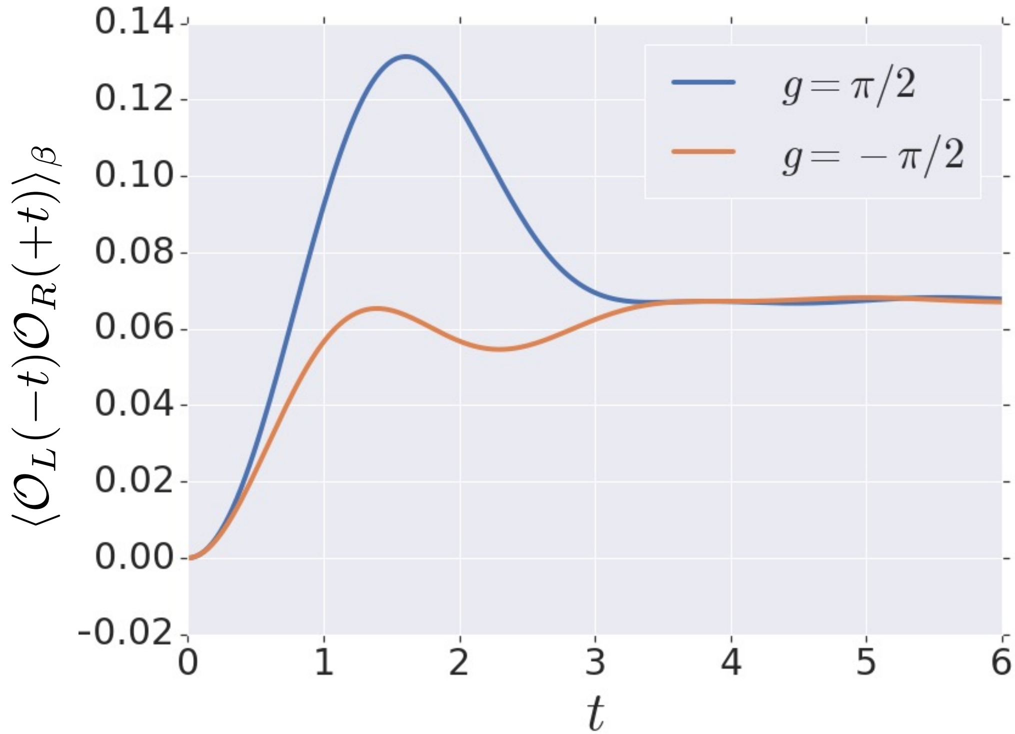
**We verify the results noticed earlier in JT gravity**

$$\boxed{\text{Moment} = \text{Size}}$$

*Bulk AdS* Boundary CFT

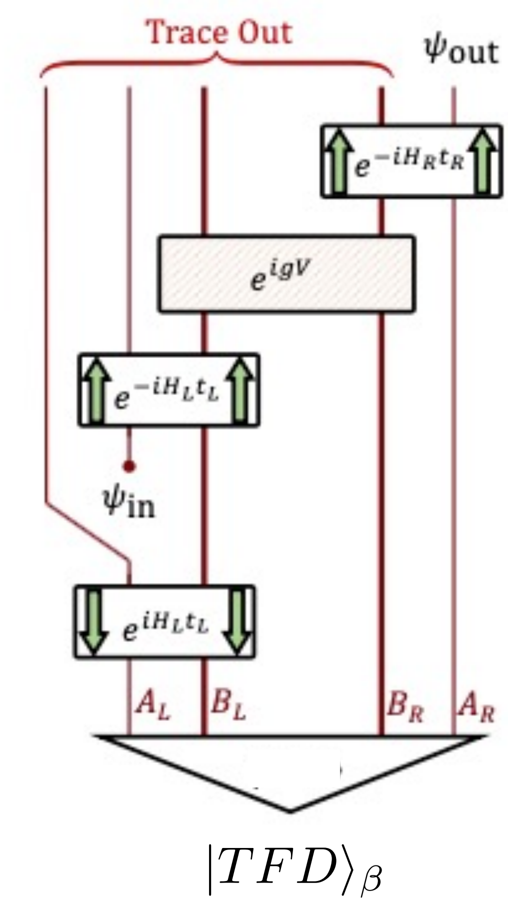
# Regime #2: size winding beyond SYK model

**Random Matrix Theory (GOE or GUE ensemble)**




**A weaker form of size-winding is responsible for capacity enhancement at low temperatures.**

# Summary




**Phase One:**

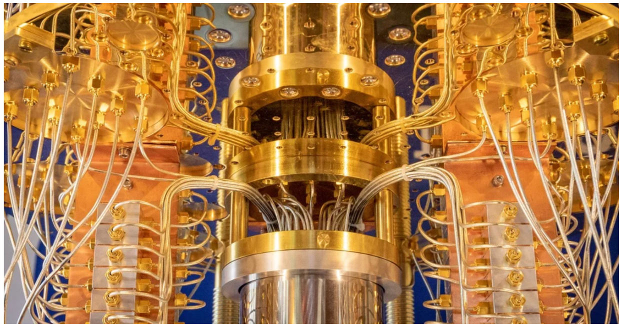
1. Infinite temperature (Bell pairs)
2. Any chaotic Hamiltonian
3. Single qubit teleportation

**Phase Two:**

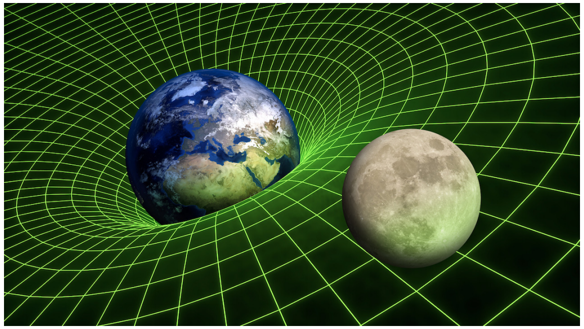
1. Finite temperature (TFD)
2. Hamiltonians that potentially have holographic duals
3. Many qubit teleportation

**(Information travels through the wormhole)**

# Final remarks: quantum gravity in the lab



**Holography**



**Quantum Devices:**

- Rydberg atoms,
- Trapped ions,
- Superconducting qubits
- And others…...

**Quantum Gravity:**

- New holographic models
- Go beyond analytic large-N methods with exp.
- Stringy effects

# Contributions

**What can we learn about quantum gravity (holography) using the tools of quantum information and computation?**

- ❖ Extend complexity = volume to evaporating black holes
- ❖ The role of python's lunch feature in the geometry to complexity
- ❖ Investigate other instances of python's lunch geometries

**Can we study deep questions about quantum gravity in the near term quantum devices?** (quantum gravity in the lab)

- ❖ Traversable wormholes, teleportation by size, and size winding
- ❖ Simulating quantum matrix models on a quantum computer
- ❖ Discovering new holographic models, protocols and observables