

Title: Exploring causality in braneworld/cutoff holography via holographic scattering

Speakers: Takato Mori

Series: Perimeter Institute Quantum Discussions

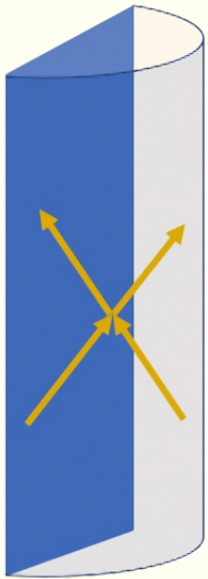
Date: November 08, 2023 - 11:00 AM

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Abstract: Holography with branes and/or cutoff surfaces presents a promising approach to studying quantum gravity beyond asymptotically anti-de Sitter spacetimes. However, this generalized holography is known to face several inconsistencies, including potential violations of causality and fundamental entropic inequalities. In this talk, we address these challenges by investigating the bulk scattering process and its holographic realization. Specifically, we propose that causality of a radially propagating excitation should be an induced one originating from a fictitious boundary behind the brane/cutoff surface. We present its consistency by checking the connected wedge theorem supported from quantum cryptography and (strong) subadditivity of holographic entanglement entropies. While the induced light cone seemingly permits superluminal signaling, we argue that this causality violation can be an artifact of state preparation in our picture. This talk is based on 2308.00739 [10.1007/JHEP10(2023)104] with Beni Yoshida.

Zoom link <https://pitp.zoom.us/j/98252951858?pwd=RVNZUjNVM2JkZXRlSXJvbEZ6cUpsUT09>

Exploring causality in braneworld/cutoff holography via holographic scattering



Takato Mori (Perimeter, YITP)



Based on [arXiv:2308.00739](https://arxiv.org/abs/2308.00739) [hep-th] (published in JHEP)
with Beni Yoshida (Perimeter)

Quantum Information Seminar @ Perimeter Institute for Theoretical Physics, November 8, 2023

Motivation

Quantum cosmology

Randall-Sundrum

String theory

D-branes

Quantum gravity

+ Quantum info

Double holography
Black hole evaporation/
microstates



brane (world)

☹ Nonlocality/superluminality [Omiya-Wei], violation of subadditivity [White-Marolf-Weinberg, TM-Yoshida]

Motivation

Quantum cosmology

Randall-Sundrum

Quantum gravity

We examine causality on branes/cutoff surfaces from **scattering/entanglement** in the bulk via **quantum information**

Black hole evaporation/
microstates

brane (world)

☹ Nonlocality/superluminality [Omiya-Wei], violation of subadditivity [White-Marolf-Weinberg, TM-Yoshida]

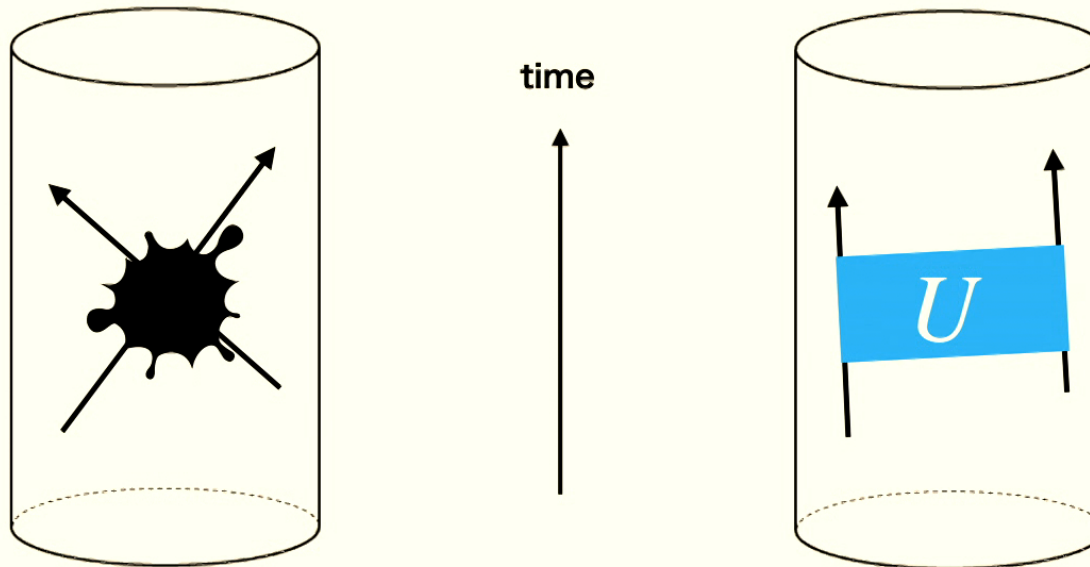
AdS/CFT correspondence

[Maldacena]

$(d+1)$ -dim. AdS spacetime \Leftrightarrow d -dim. conformal field theory (CFT)

General relativity

Quantum field theory



Holographic entanglement entropy

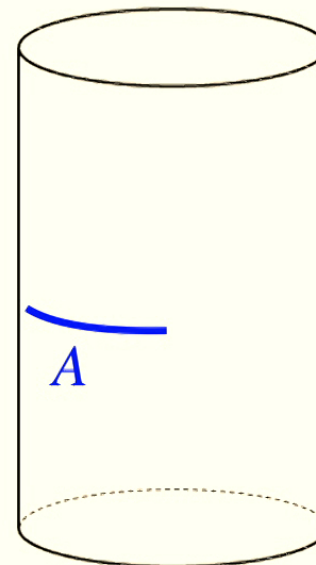
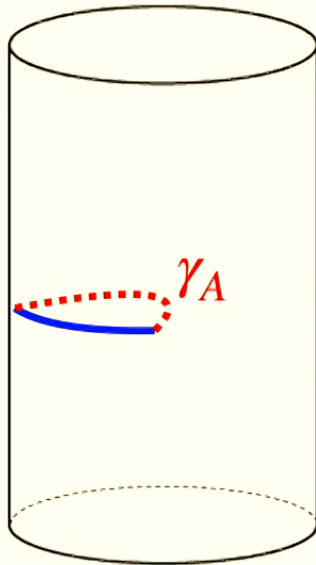
[Ryu-Takayanagi]

[Hubeny-Rangamani-Takayanagi]

Minimal surface area \Leftrightarrow Entanglement entropy

$$S_{HEE}(A) = \min_{\gamma_A} \frac{\text{Area}(\gamma_A)}{4G_N} + O(1)$$

$$S_A = -\text{tr} \rho_A \log \rho_A, \quad \rho_A = \text{tr}_{\bar{A}} \rho$$



Double holography, cutoff AdS

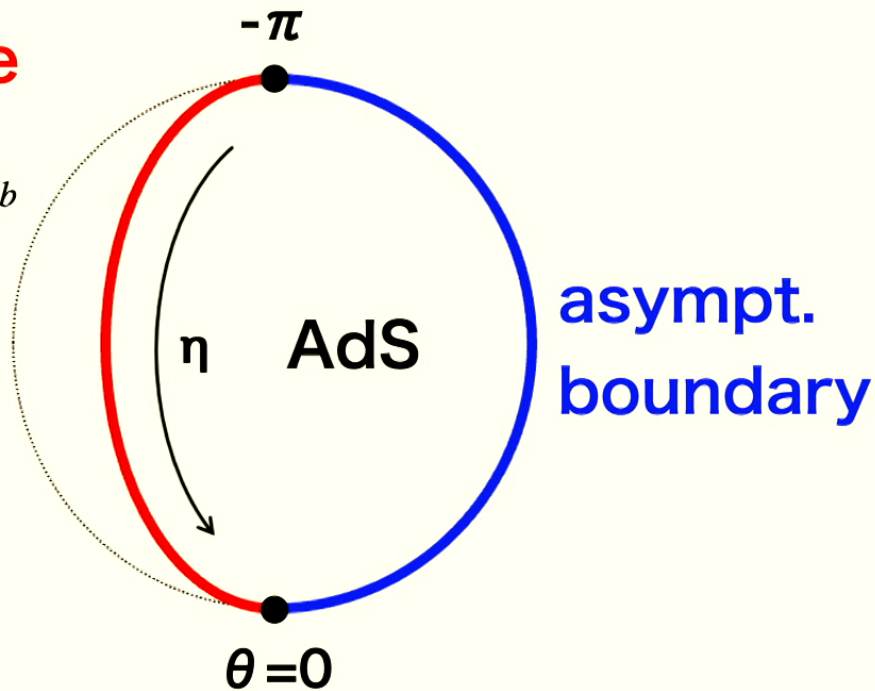
[Karch-Randall, Randall-Sundrum, Takayanagi]

[McGough-Mezei-Verlinde]

End-of-The-World
ETW brane

$$K_{ab} - Kh_{ab} = Th_{ab}$$

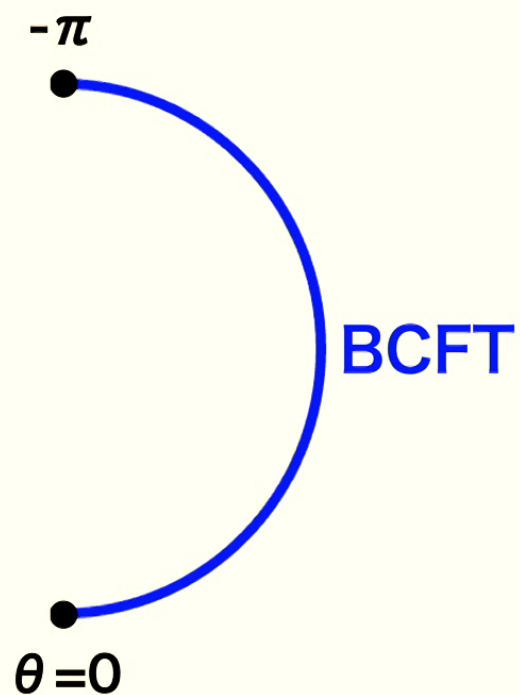
$$(K_{ab} = \nabla_a n_b)$$



Double holography, cutoff AdS

[Karch-Randall, Randall-Sundrum, Takayanagi]

[McGough-Mezei-Verlinde]



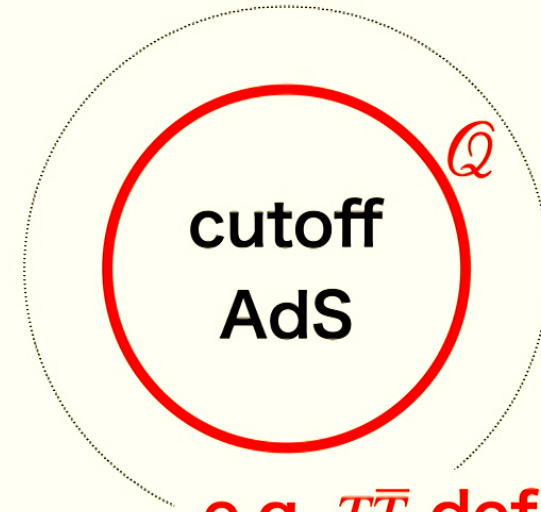
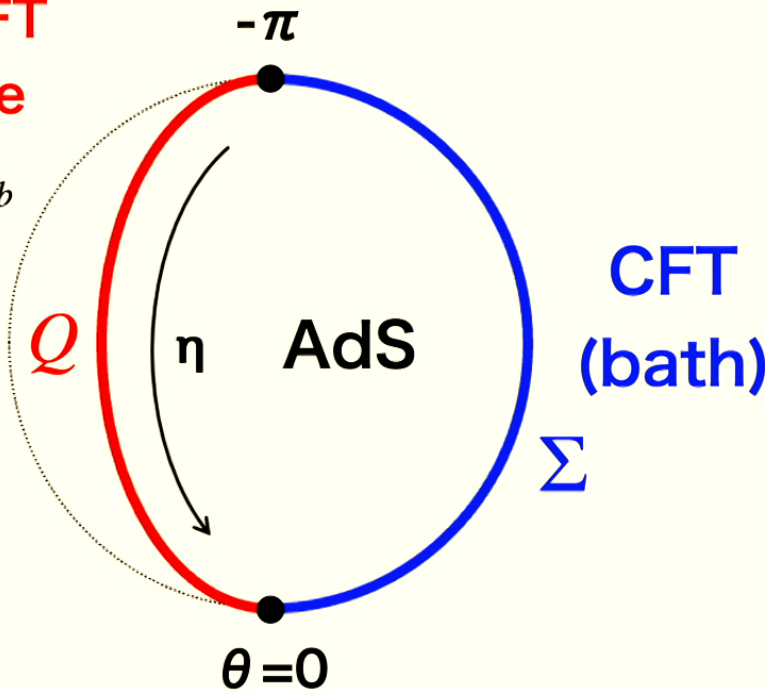
Double holography, cutoff AdS

[Karch-Randall, Randall-Sundrum, Takayanagi]
 [McGough-Mezei-Verlinde]

**Gravitating QFT
 on ETW brane**

$$K_{ab} - Kh_{ab} = Th_{ab}$$

$$(K_{ab} = \nabla_a n_b)$$

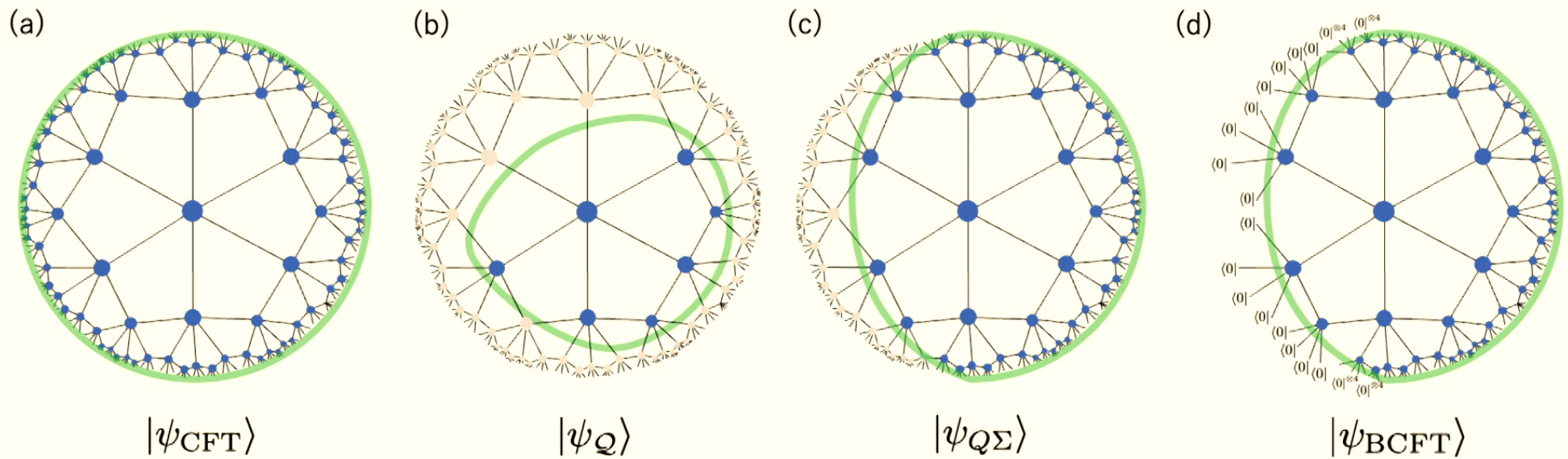


**e.g. $T\bar{T}$ -deformed
 CFT**

Does a quantum theory on $Q \cup \Sigma$ or Q make sense?

Tensor network picture

[TM-Yoshida]



Puzzles about causality and entanglement on \mathcal{Q}, \mathcal{Q}

We focus on three puzzles and propose a resolution.

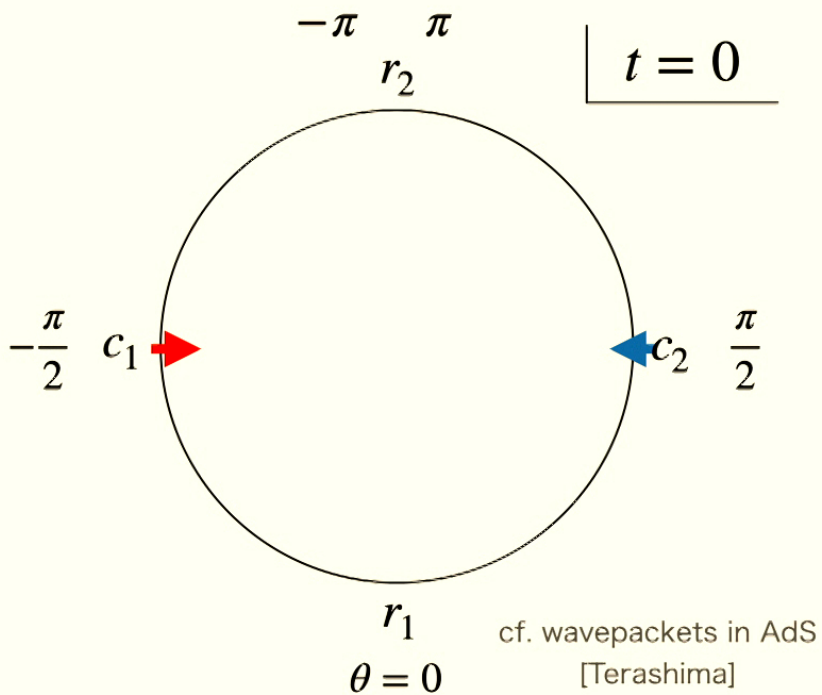
1. **Connected wedge theorem** [May] for 2-to-2 scattering between \mathcal{Q}, \mathcal{Q}
 - ← **Quantum cryptography**
 - Nonlocal realization of quantum task on \mathcal{Q}, \mathcal{Q}
 - Proposal: Induced light cone**
2. Violation of **subadditivity** of holographic entanglement entropy on \mathcal{Q}, \mathcal{Q}
 - ← **Validity of quantum mechanics on \mathcal{Q}, \mathcal{Q}**
 - Entanglement structure?
3. **Superluminal signaling** (1-to-1 'scattering') [Omiya-Wei]
 - ← **Physical interpretation of acausality**

Connected wedge theorem in AdS/CFT:
scattering in AdS \Rightarrow entanglement on boundary

Scattering in the bulk implies connected entanglement wedge

[May 2019]

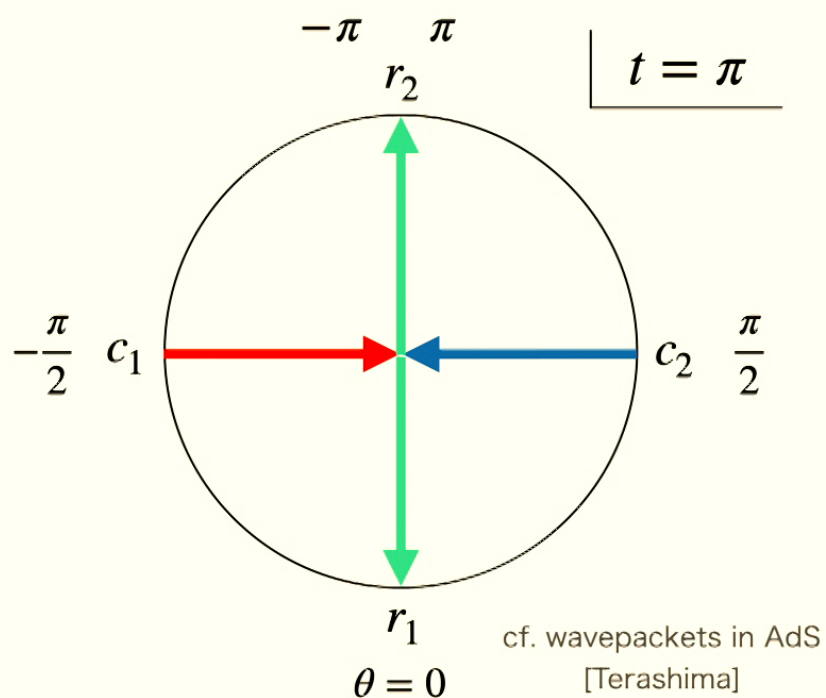
Consider when a direct scattering in the bulk (AdS) is possible but not on the boundary



Scattering in the bulk implies connected entanglement wedge

[May 2019]

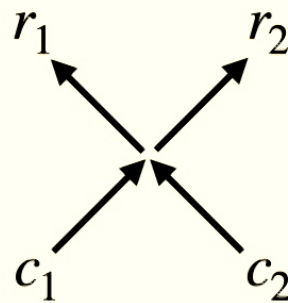
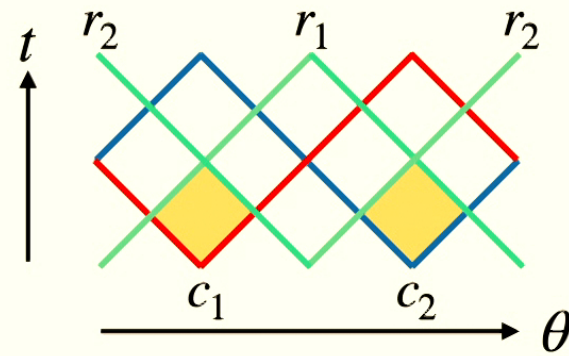
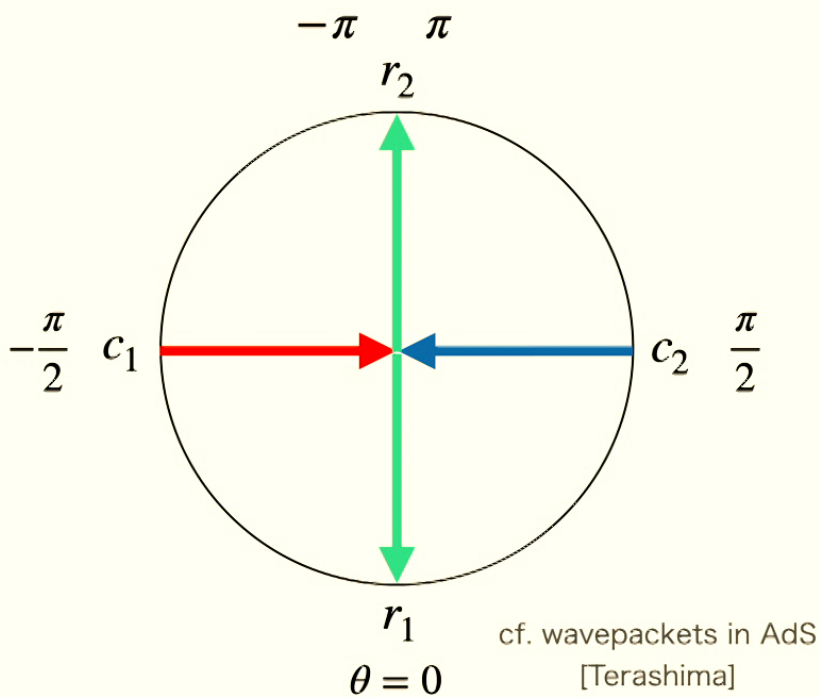
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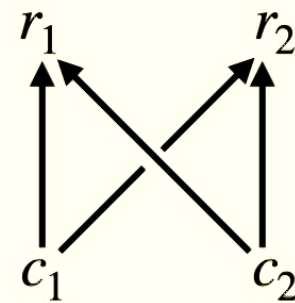
Scattering in the bulk implies connected entanglement wedge

[May 2019]

Consider when a direct scattering in the bulk (AdS) is possible but not on the boundary



Bulk

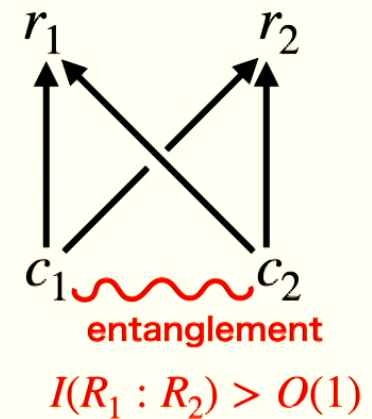
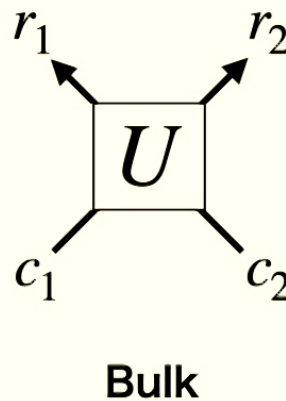
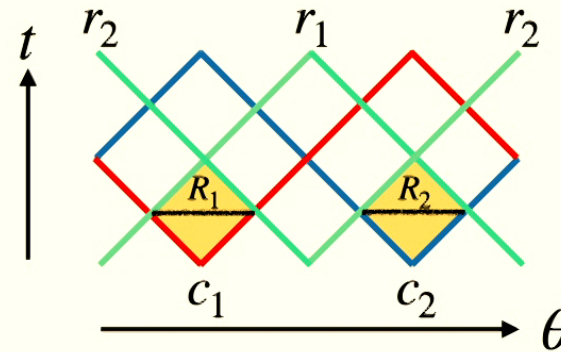
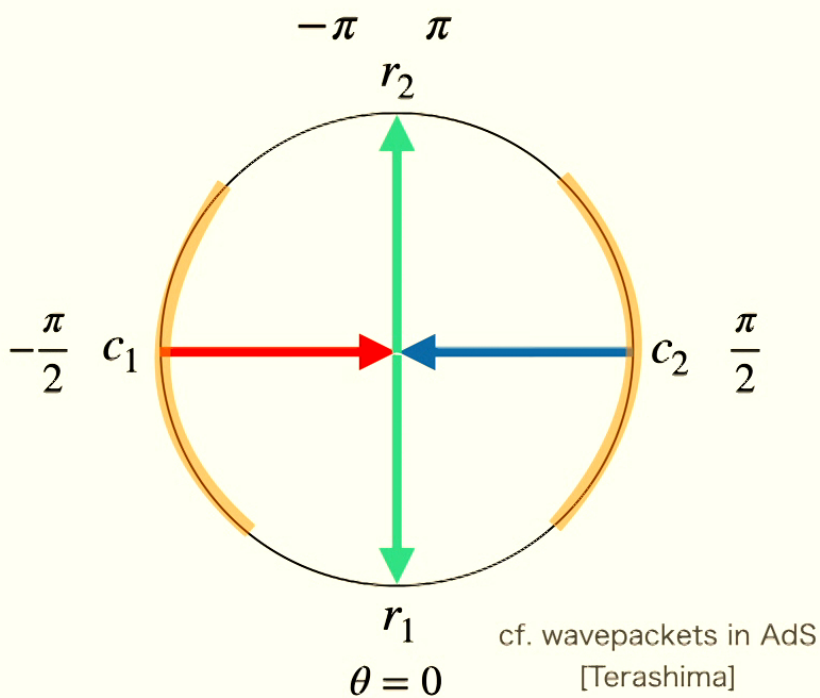


Boundary

Scattering in the bulk implies connected entanglement wedge

[May 2019]

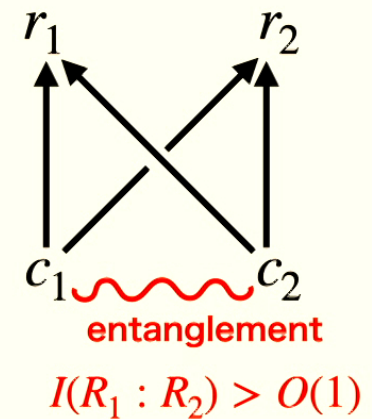
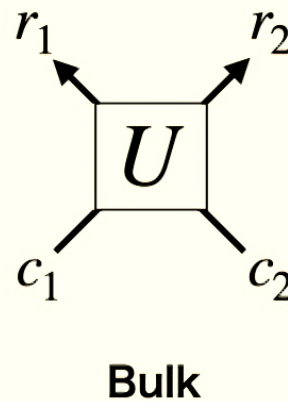
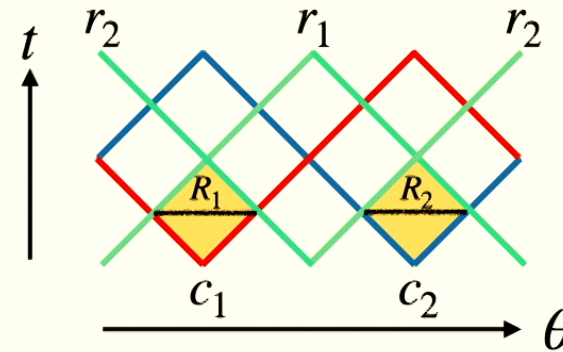
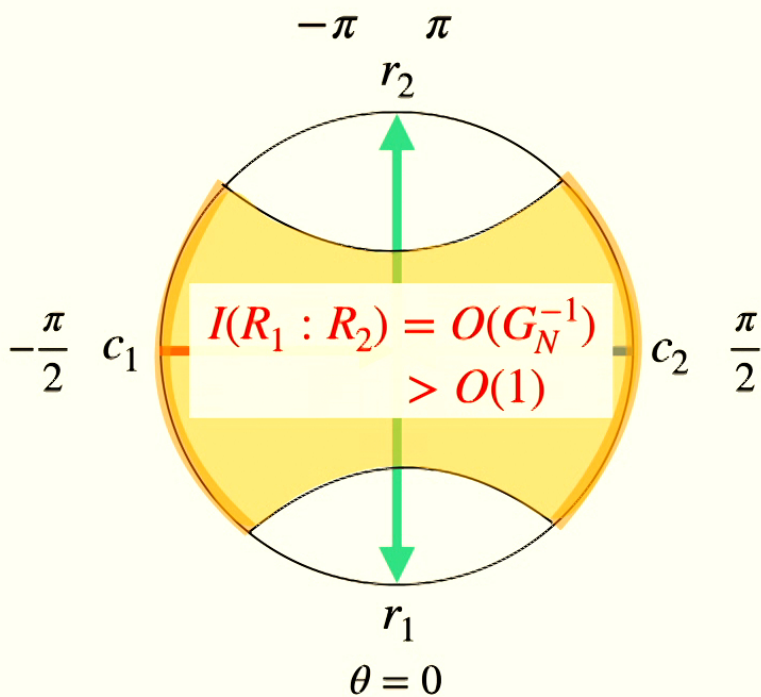
Consider when a direct scattering in the bulk (AdS) is possible but not on the boundary



Scattering in the bulk implies connected entanglement wedge

[May 2019]

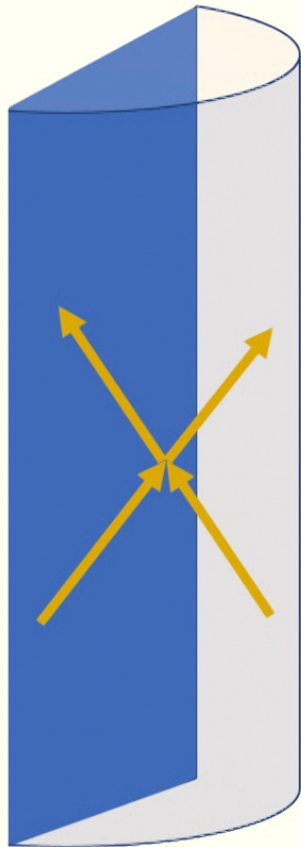
Consider when a direct scattering in the bulk (AdS) is possible but not on the boundary



Connected wedge theorem for **general surface**:
scattering in AdS \Rightarrow entanglement on **surface**

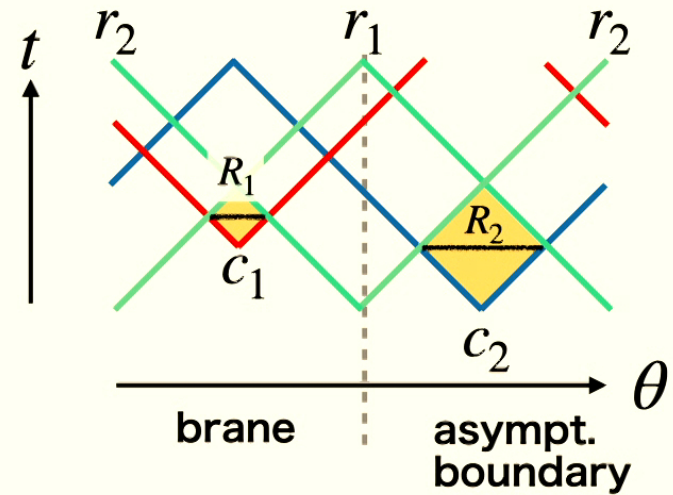
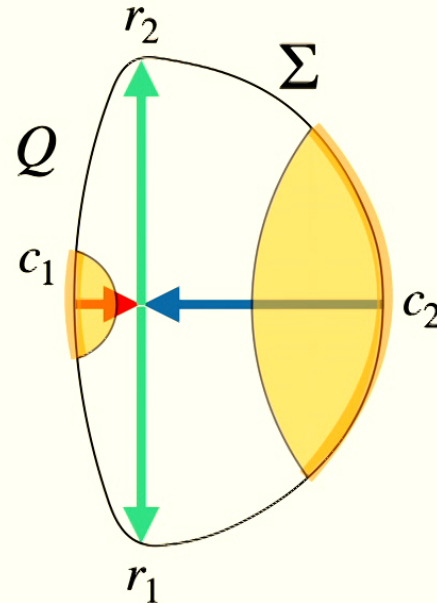
Puzzle 1: Disconnected entanglement wedge

[TM-Yoshida]



t ↑
2-to-2 scattering between brane Q and boundary

A naive extension fails:

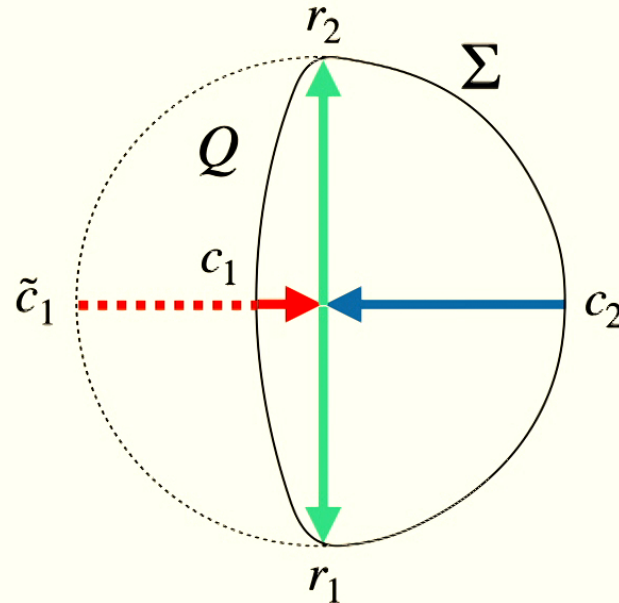


Proposal: Induced light cone

[TM-Yoshida]

Everything is well-defined on the asymptotic boundary.

Define the signals from/to \mathcal{Q} , \mathcal{Q} from a fictitious asymptotic boundary

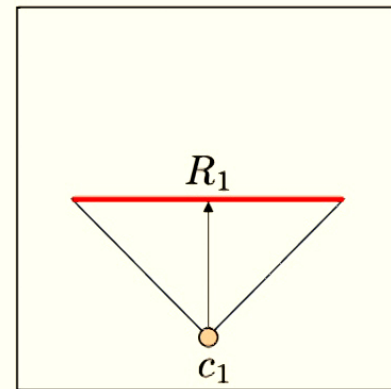
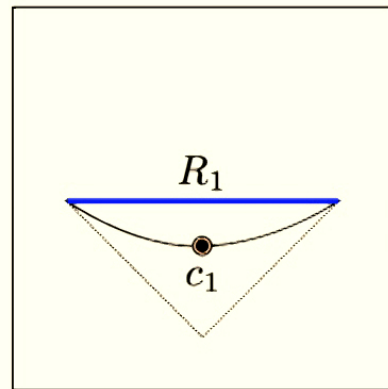
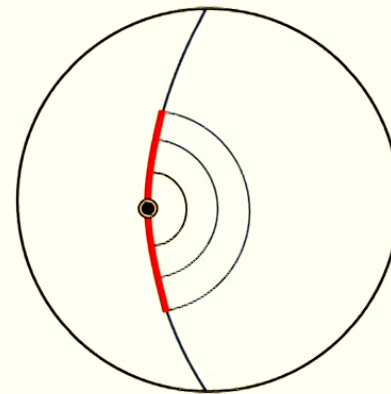
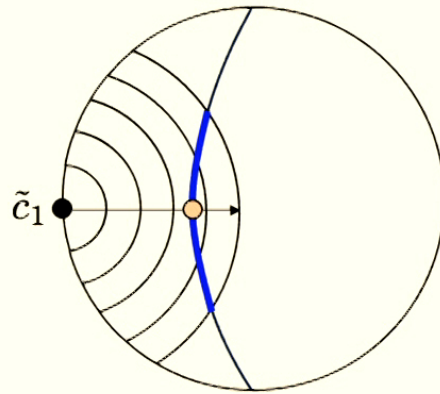


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Proposal: Induced light cone

[TM-Yoshida]

This changes the apparent causality on \mathcal{Q}



the redshift is $z \equiv \frac{\nu_R}{\nu_E} - 1$

frequency is an inverse time

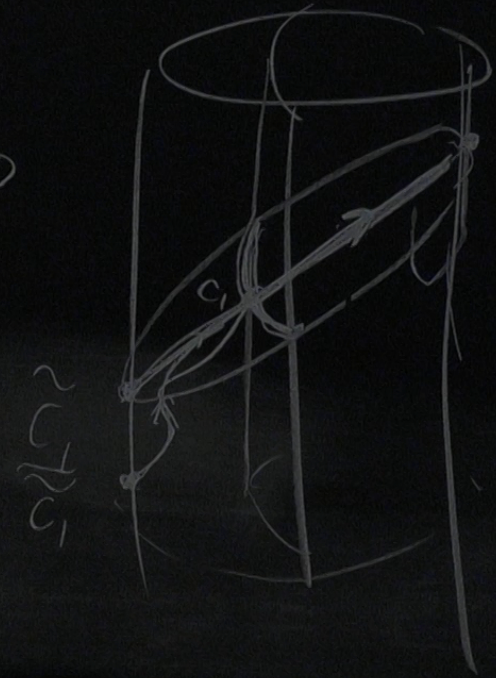
$$\rightarrow \frac{\nu_R}{\nu_E} = \left(\frac{1}{dt_R}\right) \left(\frac{1}{dt_E}\right)^{-1} = \frac{dt_E}{dt_R}$$

$$\nabla_\mu \nabla_\nu F^{\mu\nu} = \nabla_\nu J^\nu = 0$$

$$\nabla_\mu \int d^d \vec{x} \sqrt{-g(\vec{x}, t)} J^\mu(x)$$

$$\nabla_\mu J^\mu = 0$$

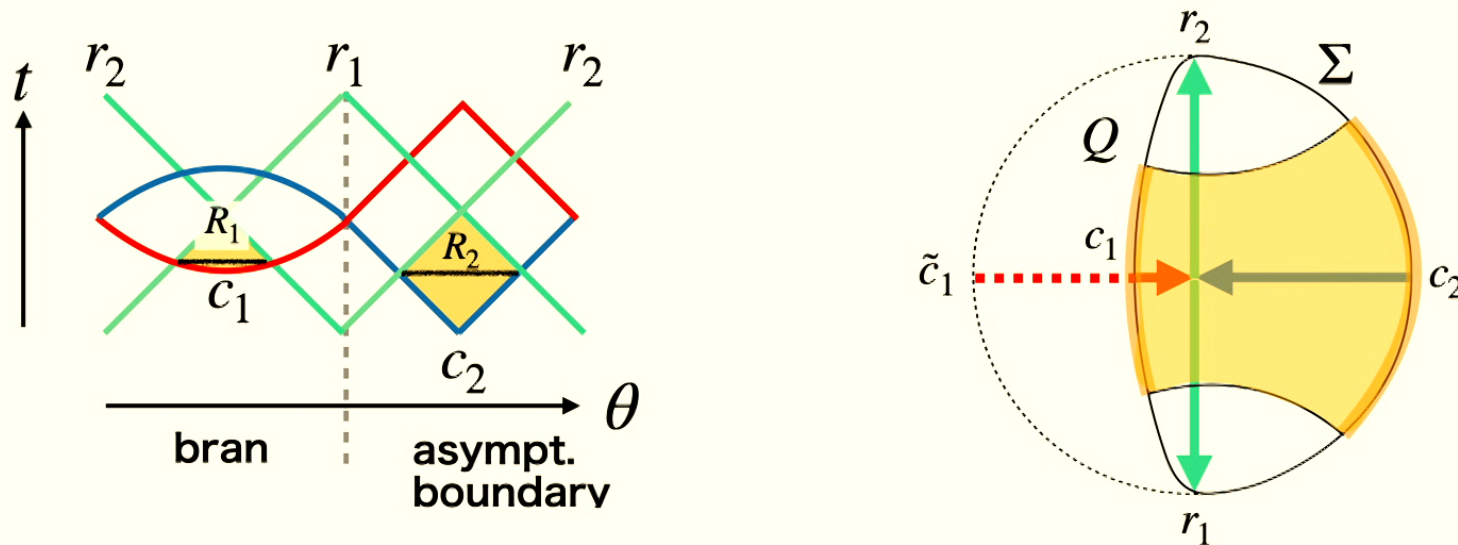
changes in the gravitational field can induce a redshift



Induced causal diamond \Rightarrow Connected wedge theorem

[TM-Yoshida]

Modification in causality on $Q \Rightarrow$ modification of domain of dependence
 \Rightarrow enlarged subregion relevant to nonlocal task



This can be proven for any convex surfaces in asympt. AdS with some reasonable assumptions using the focusing theorem

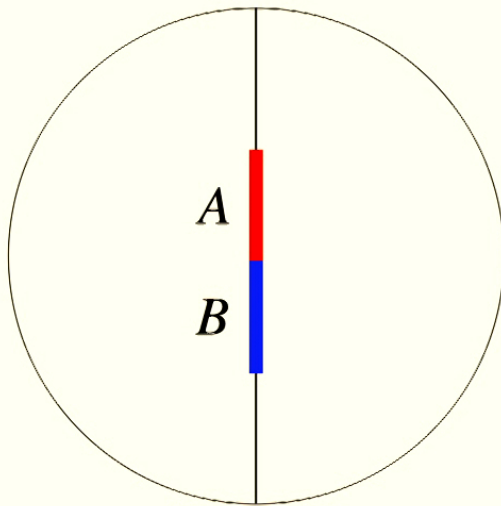
Subadditivity on the brane from induced causal diamond

Puzzle 2: Violation of subadditivity on the brane

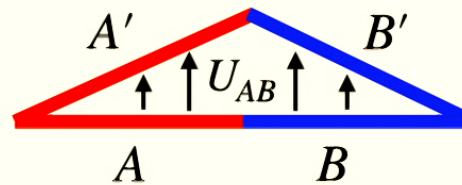
cf. [Grado-White, et al.] [Lewkowycz-Liu, et al.]

For simplicity, let us consider a tensionless brane.

Assuming holographic entanglement entropy formula, $S_A + S_B = S_{AB}$.



By boosting AB , holographic entanglement entropies violate subadditivity: $S_{A'} + S_{B'} < S_{A'B'}$

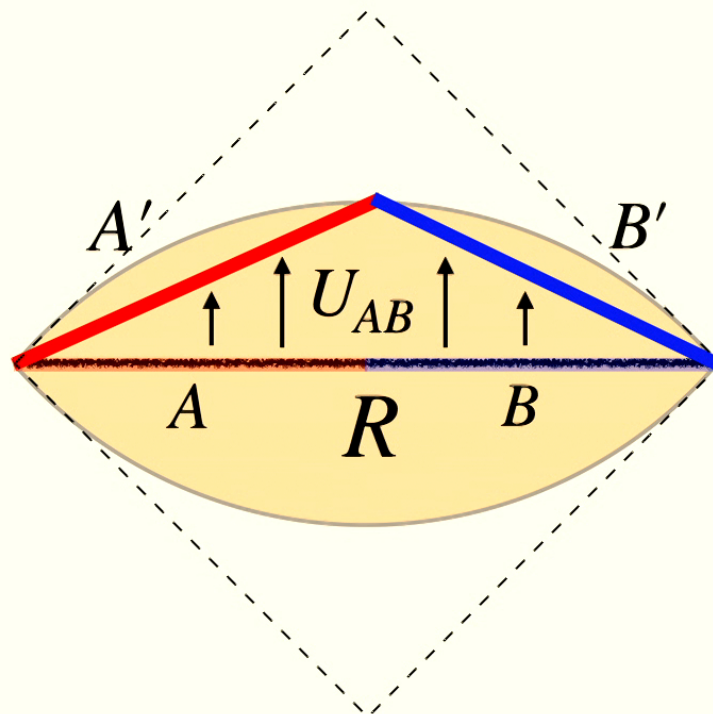


$$S_{A'} + S_{B'} < S_A + S_B \leq S_{AB} = S_{A'B'}$$

Any quantum systems must satisfy SA. What's wrong with this?

Puzzle 2: Violation of subadditivity on the brane

cf. [Grado-White, et al.] [Lewkowycz-Liu, et al.]



Within the *induced* causal diamond, SA and SSA hold!

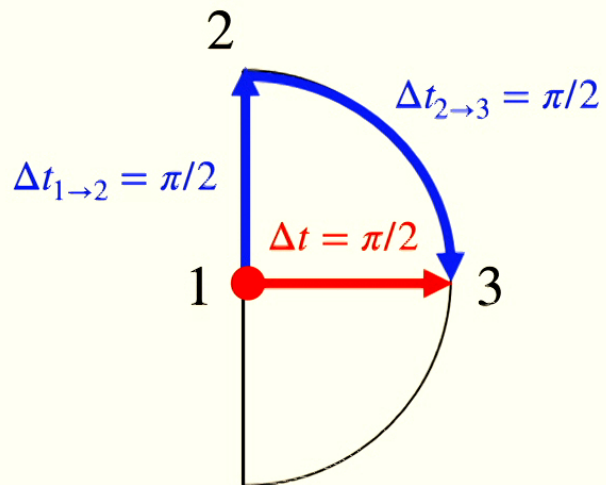
(Can be proven generically using techniques from [White-Marolf-Weinberg])

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Superluminality is apparent or real?

Puzzle 3: Superluminal signaling [Omiya-Wei]

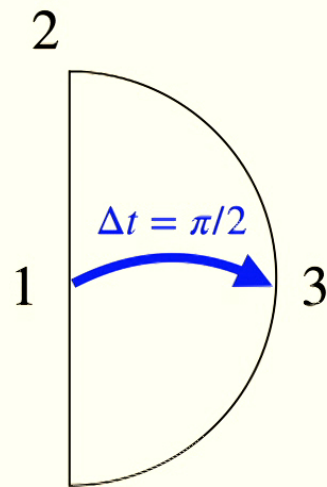
∃ Bulk shortcut violating the Gao-Wald thm ⇒ superluminal signaling?



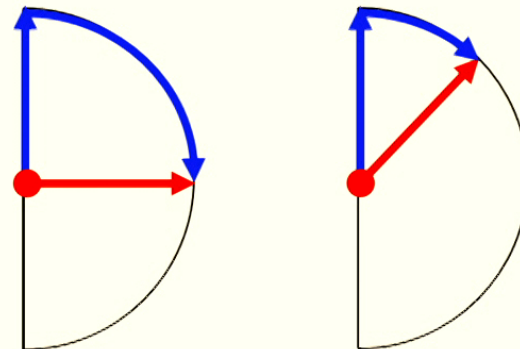
$$\Delta t_{1 \rightarrow 2} + \Delta t_{2 \rightarrow 3} > \Delta t$$

Puzzle 3: Superluminal signaling [Omiya-Wei]

∃ Bulk shortcut violating the Gao-Wald thm \Rightarrow superluminal signaling?
One resolution by [Omiya-Wei]: Nonlocal coupling (microscopic wormhole)



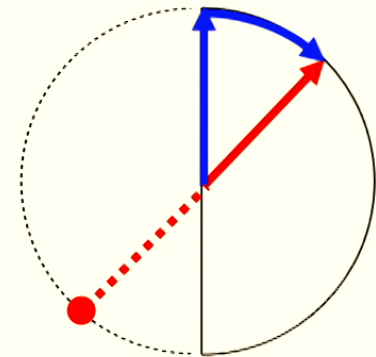
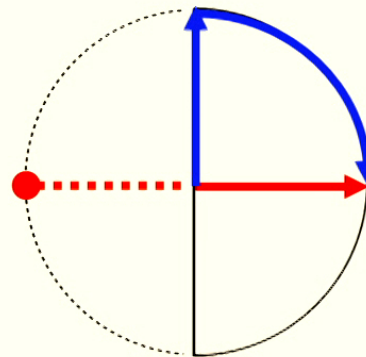
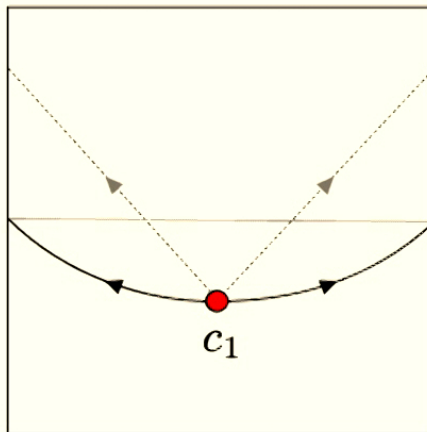
This requires fine tuning of couplings...
Relevant microscopic wormholes depends on the direction



Puzzle 3: Superluminal signaling

Instead, we explain this by “superluminal signaling” from the induced causality.

Direction dependence is manifest as the location of fictitious excitations



Puzzle 3: Superluminal signaling

Superluminal signaling along the induced light cone?

↕ tension

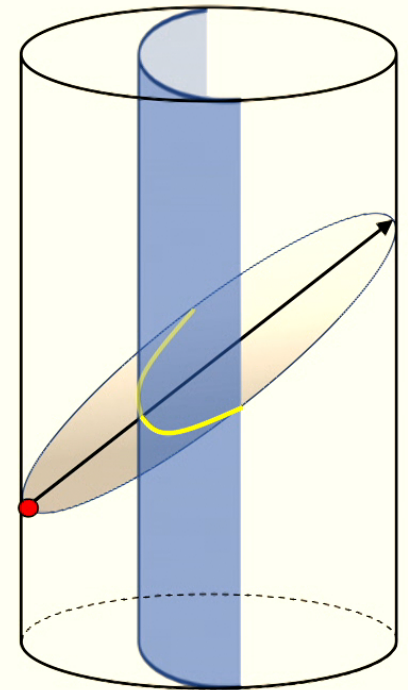
$[O, O']_Q = 0$, where O, O' are spacelike separated [Omiya-Wei]

Information is actually not traveling along the induced light cone. **No violation of causality**

The signal is not instantaneously prepared by a local excitation

→ Prepared with the fictitious region.

Information is nonlocally shared before signaling.



Summary

With induced causality, we can explain

- **Connected wedge theorem with a generalized boundary** (brane Q , cutoff surface \mathcal{Q}) as supported from QI argument
- **(Strong) subadditivity** of holographic entanglement entropy on Q, \mathcal{Q}
- Apparent **superluminal signaling** due to bulk shortcuts as **state preparation** without giving up locality and holographic entanglement entropy formula.

The induced causality is necessary to justify the generalized holography from a local quantum theory on a brane/cutoff surface.

This indicates incompatibility between

- Standard causality \leftrightarrow Trapped excitations
- Holographic entanglement entropy \leftrightarrow Trapped & radially propagating excitations