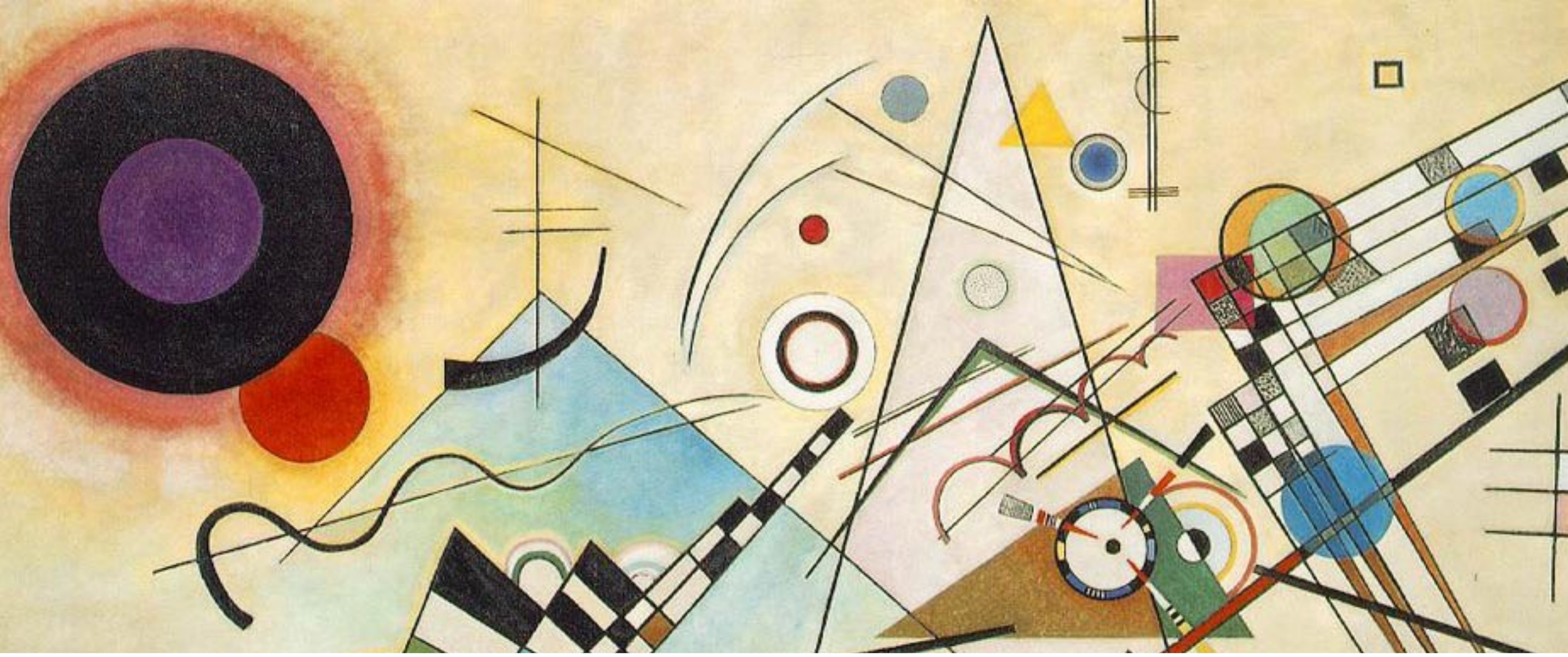


BLACK HOLE INTERIORS AND THE NATURE OF TIME

Lampros Lamprou
University of British Columbia

Question 1:

What does the interior of a black hole look like?

Question 2:

What is the nature of time measured by an observer?

Question 1:

What does the interior of a black hole look like?

In Quantum Gravity

Question 2:

What is the nature of time measured by an observer?

Question 1:

What does the interior of a black hole look like?

In Quantum Gravity: Entire Universe is a Quantum System

Question 2:

What is the nature of time measured by an observer?

Seeing inside black holes is version of the information puzzle!

In Quantum Gravity: Entire Universe is a Quantum System

Question 2:

What is the nature of time measured by an observer?

Seeing inside black holes is version of the information puzzle!

In Quantum Gravity: Entire Universe is a Quantum System

Any observer is a subsystem of the Universe

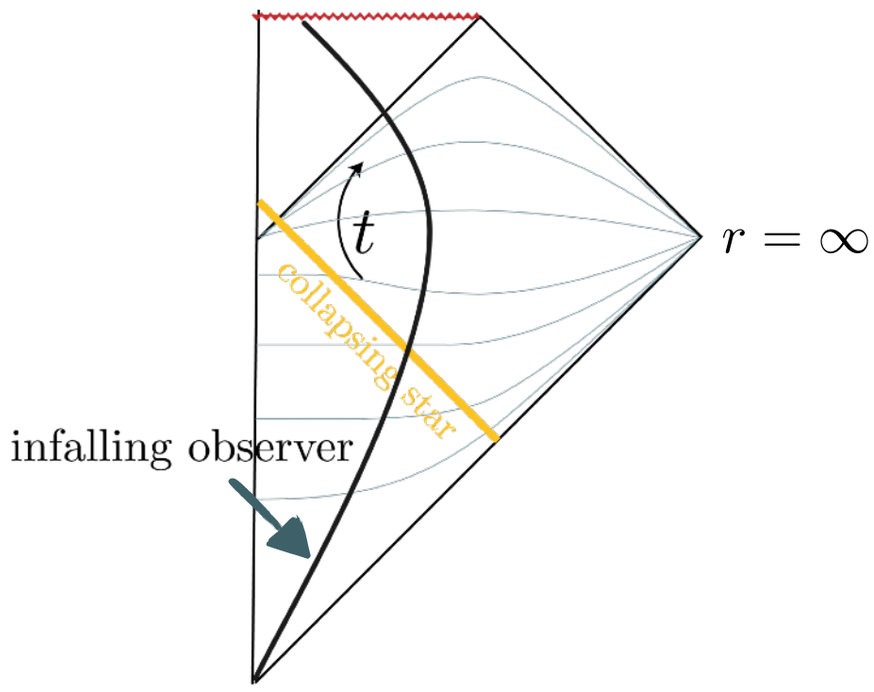
Time experienced by observers is "emergent"!

My contribution:

(a) How to select a subsystem as a frame of reference.

(b) Understand how to evolve the Universe relative to it.

(c) Follow an infalling observer into a black hole!



Address a version of the black hole information problem!

Bring "relativity" back into (quantum) gravity

Quantum theory

Fixed reference frame

One preferred Hamiltonian

General Relativity

Observer "democracy"

All times on equal footing

General Theory of Relativity

Black hole horizon: (1) Point of no return!

(2) Otherwise not a special place

i.e. black holes have smooth interiors

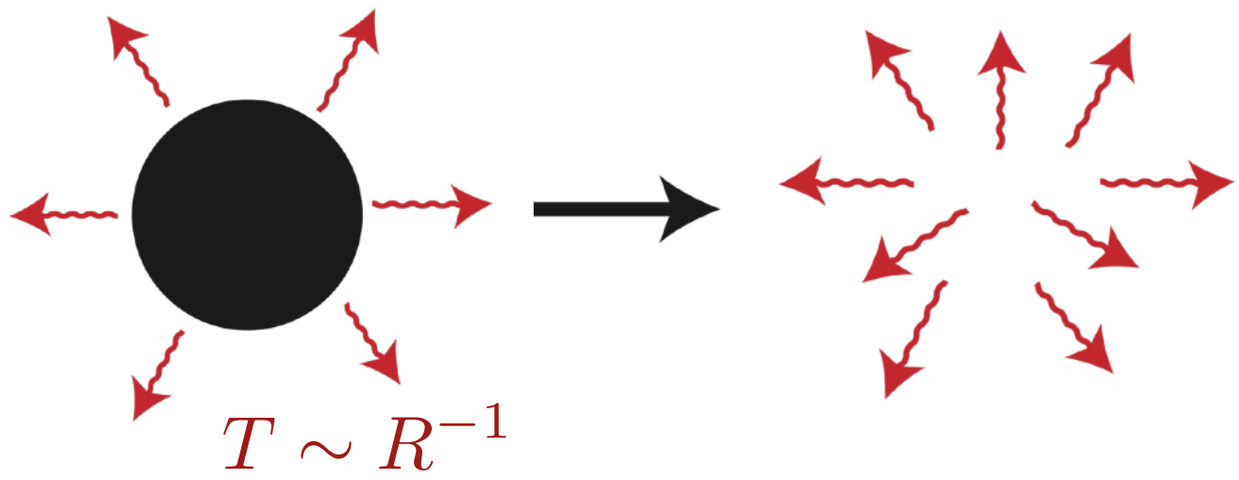
General Theory of Relativity

+ Quantum mechanics

↓

Slowly leak out energy and information

(Hawking radiation)



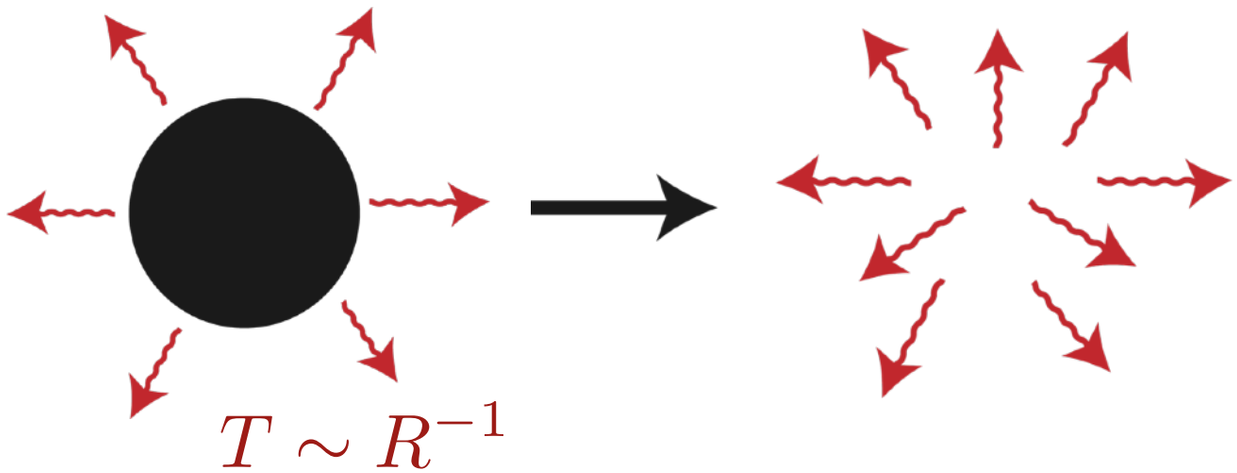
General Theory of Relativity

+ Quantum mechanics

↓

Slowly leak out energy and information

(Hawking radiation)



Information Puzzle:

Reversibility of evaporation ⟷ tension! ⟷ existence of a smooth interior

To resolve information problem:

1) Find a quantum description of a Universe with black holes

2) Perform a measurement in the interior

e.g. local energy density (diagnose smoothness)

To resolve information problem:

1) Find a quantum description of a Universe with black holes

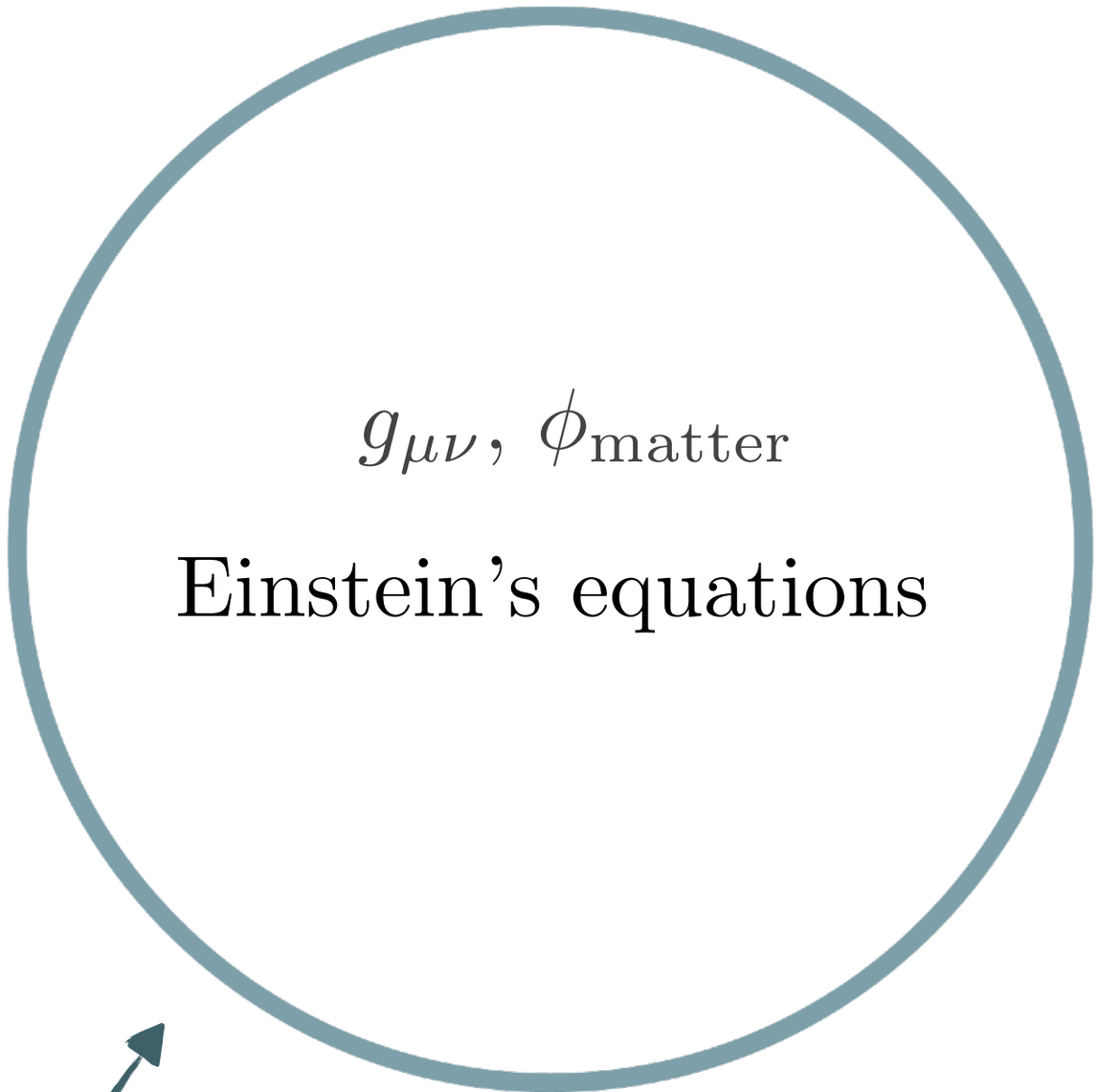
2) Understand evolution in the reference frame of an infalling observer

3) Perform a measurement in the interior
e.g. local energy density (diagnose smoothness)

Step 1:

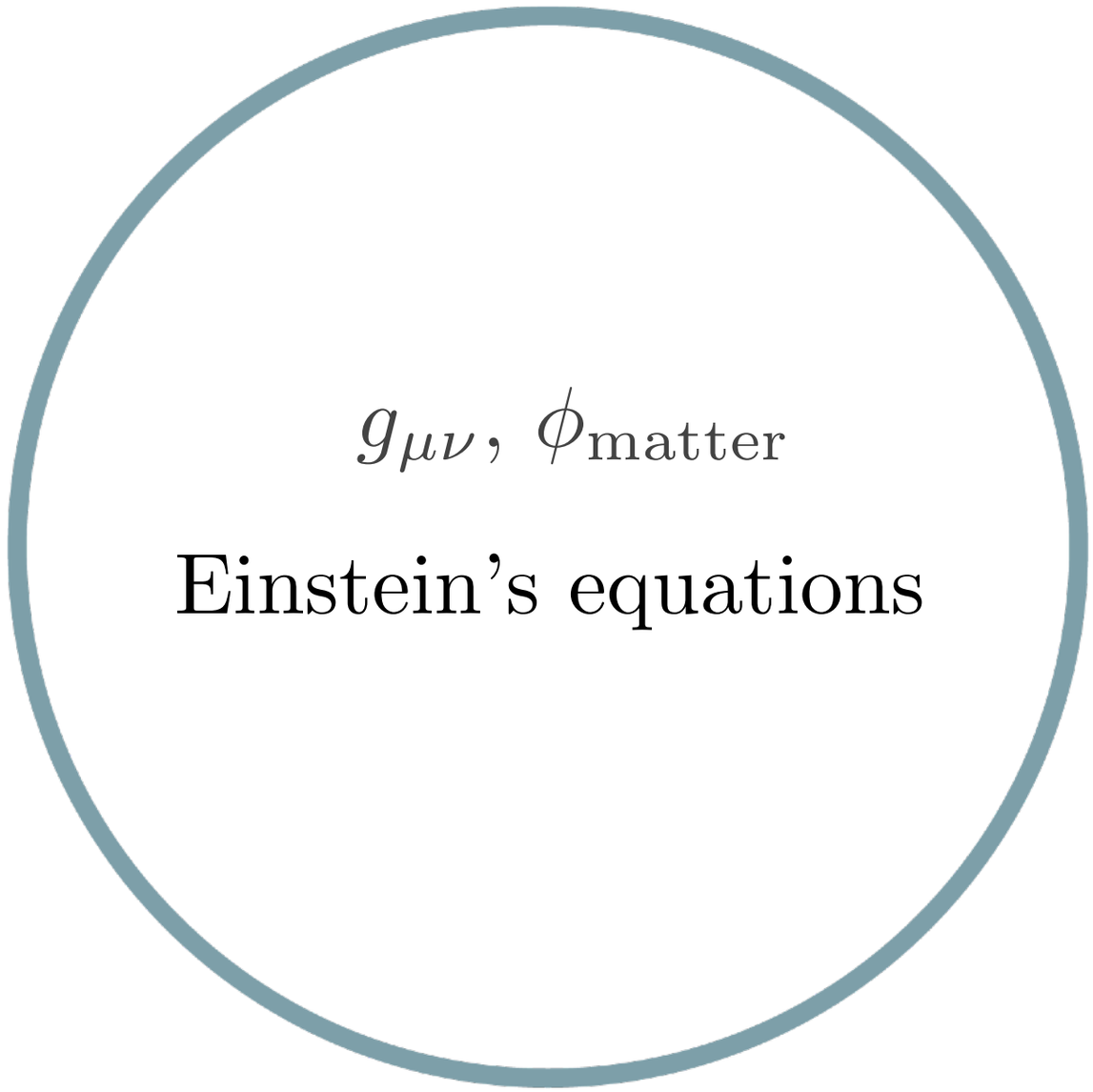
A Quantum Universe

A Universe in a Box



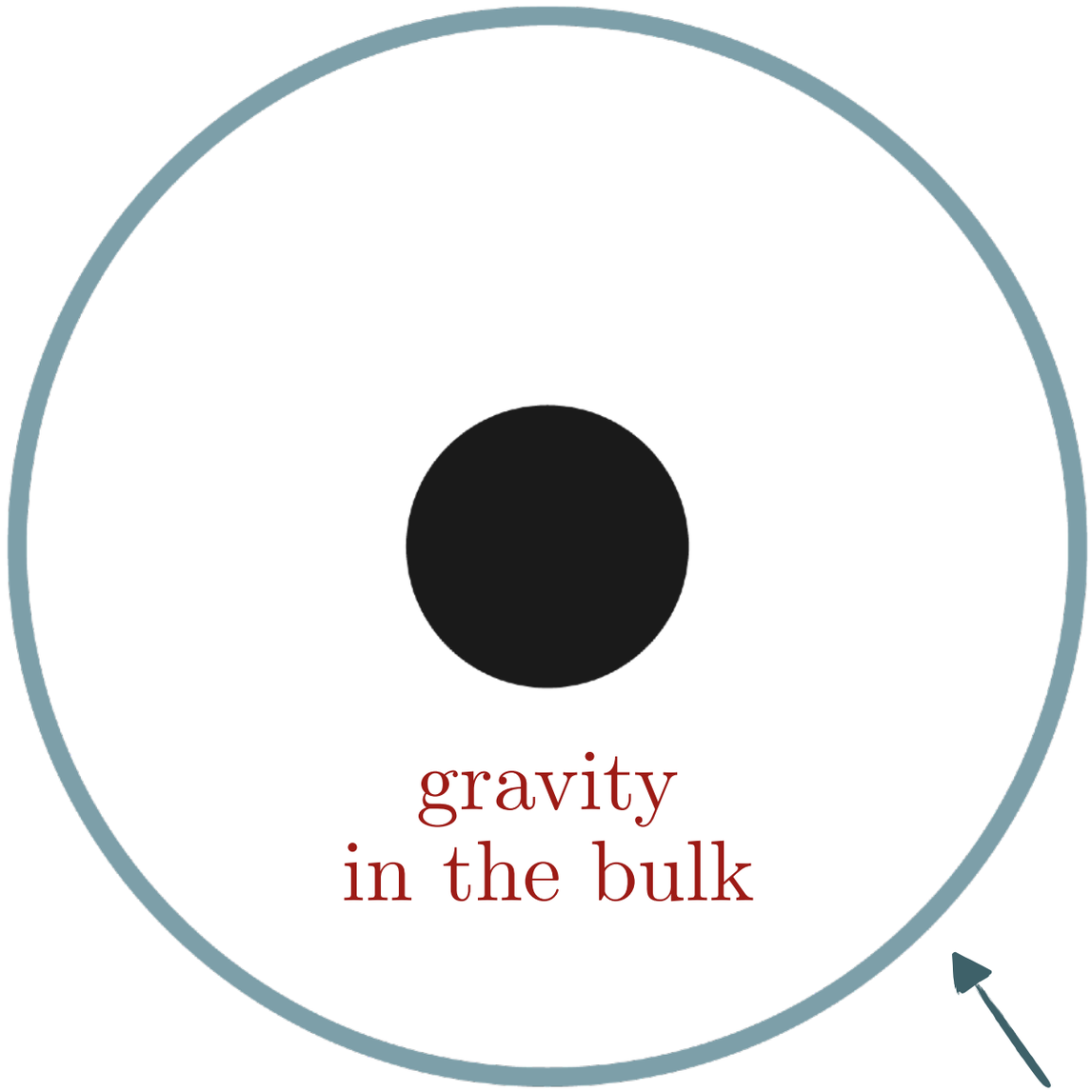
Reflective boundary conditions

Asymptotically Anti-de Sitter space

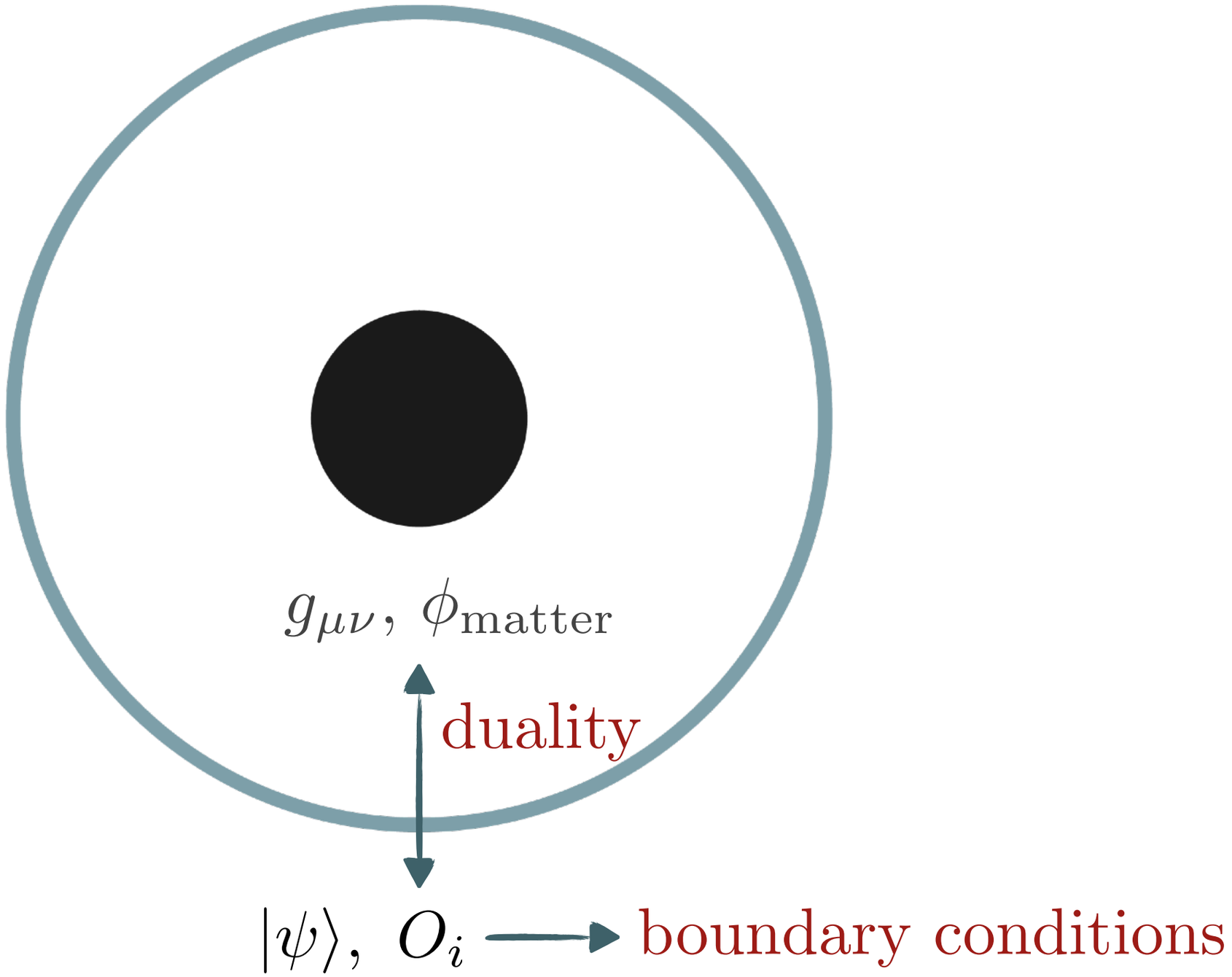


Cosmological Constant < 0

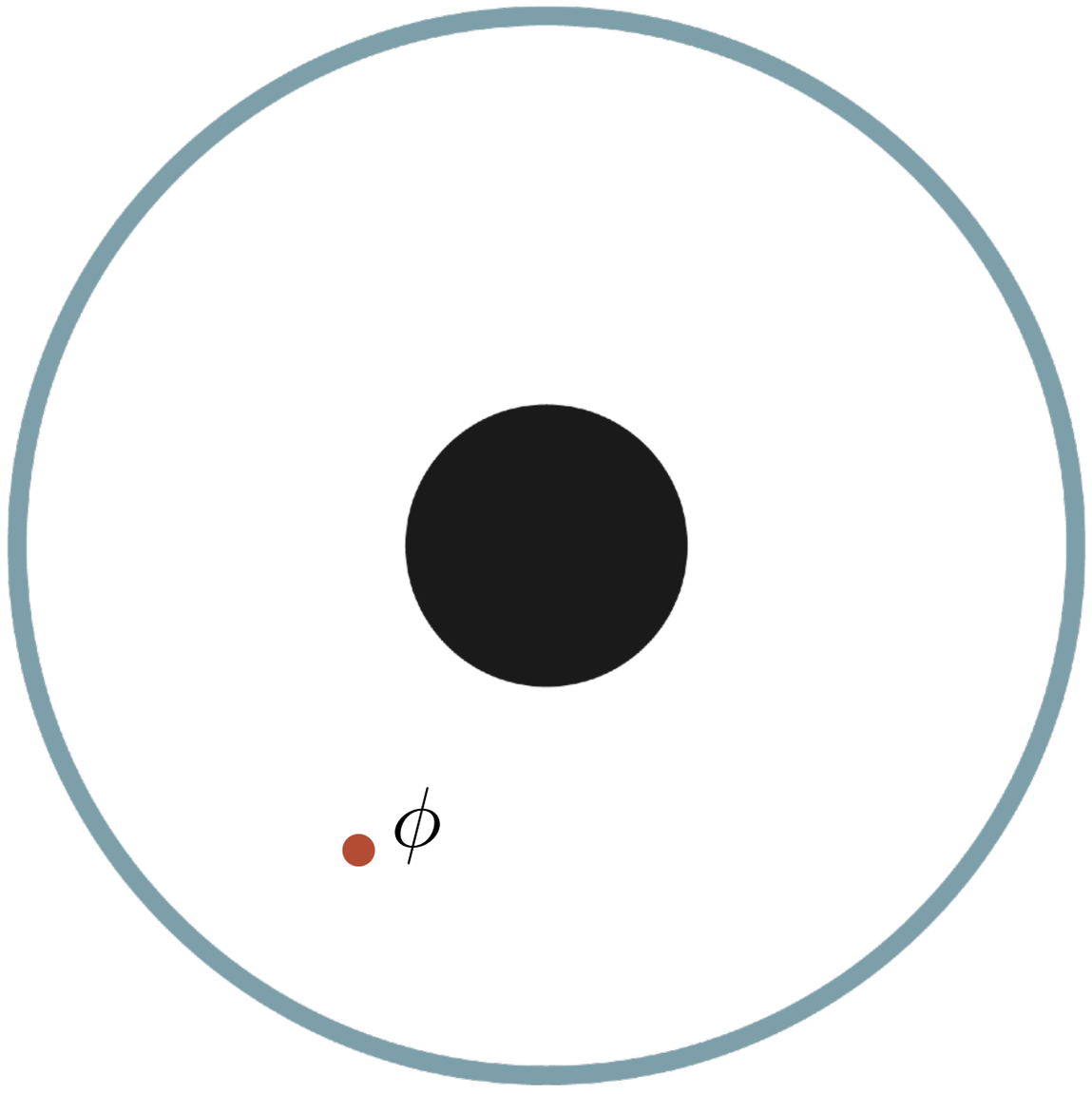
Black hole in
Asymptotically Anti-de Sitter space



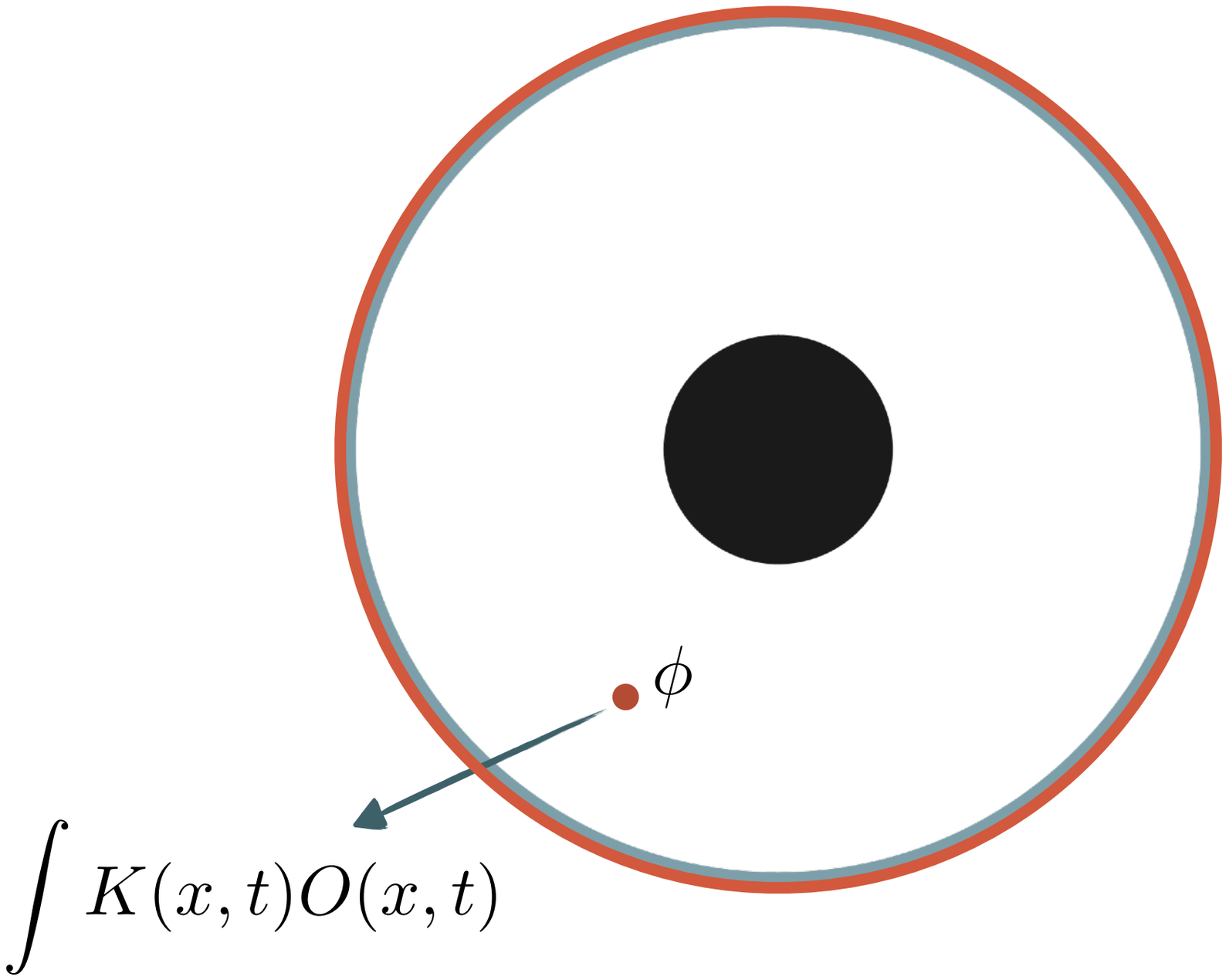
Black hole in
Asymptotically Anti-de Sitter space



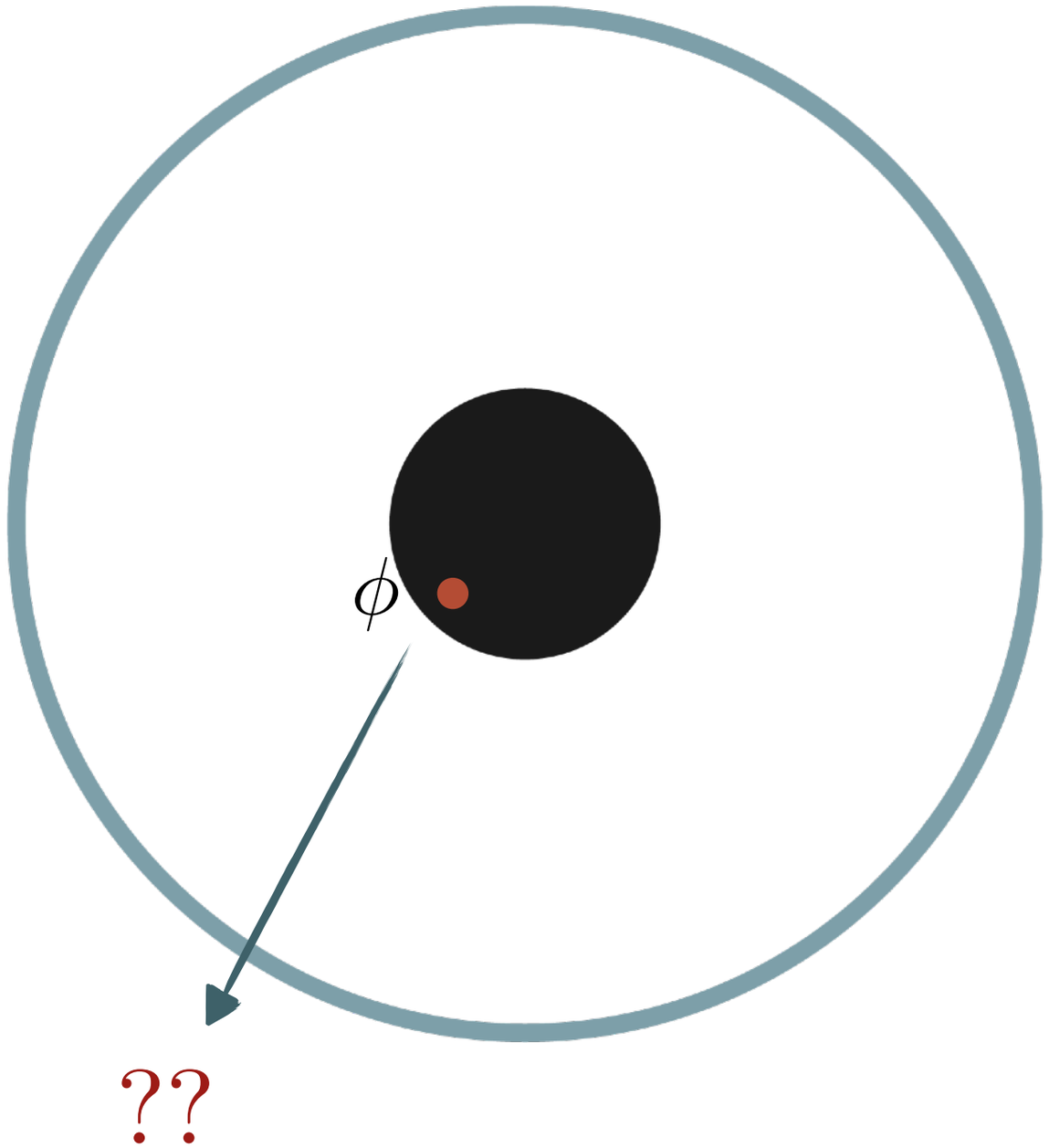
Black hole in
Asymptotically Anti-de Sitter space



Black hole in
Asymptotically Anti-de Sitter space



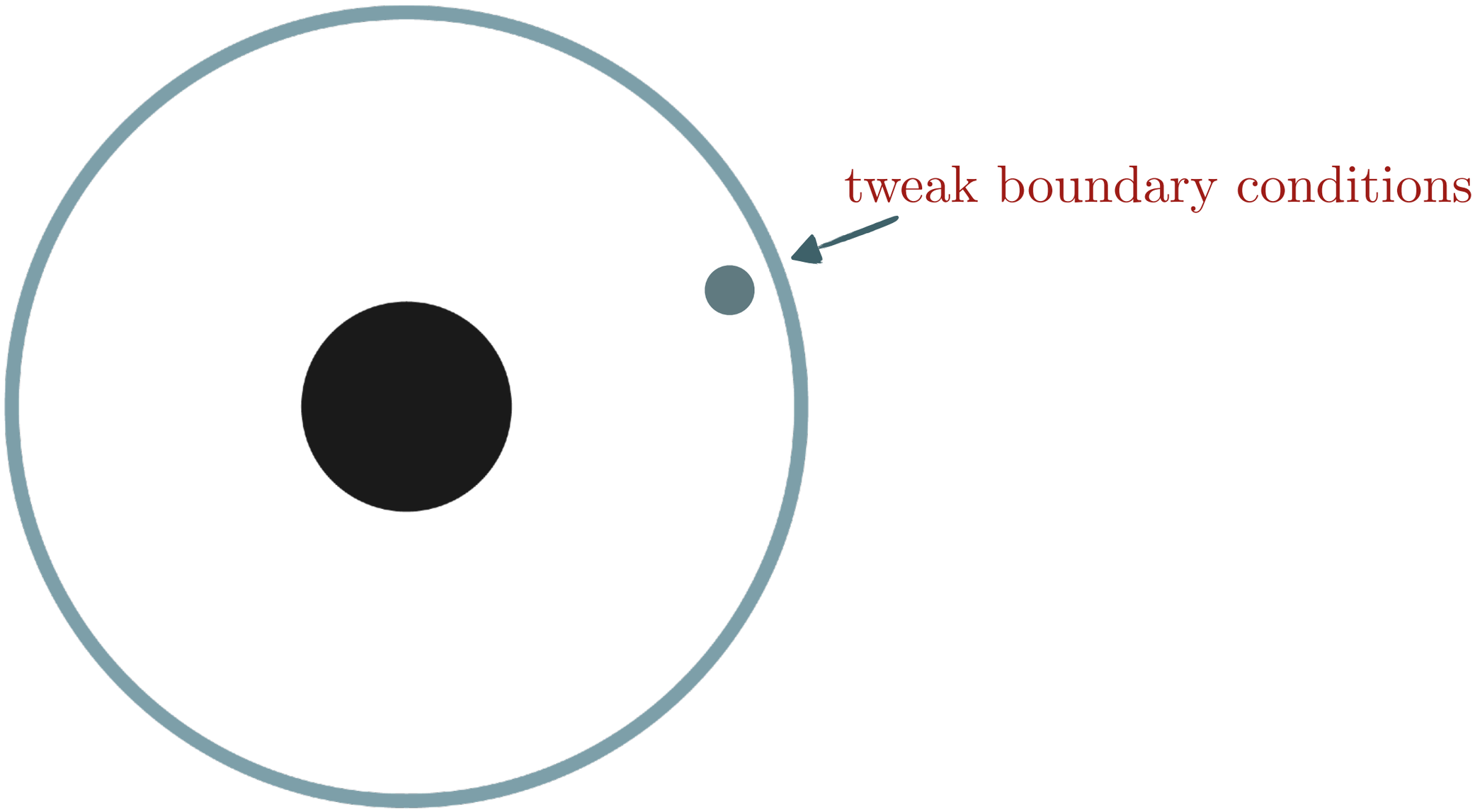
Black hole in
Asymptotically Anti-de Sitter space



Step 2:

Jumping inside the black hole and the problem of time

Introduce a probe observer



The "Observer"

1) Localized probe

2) Sufficiently large number of microstates

3) In local thermal equilibrium

Our proposal

Entire AdS Universe with probe → dual quantum state $|\psi\rangle$

State of the Universe relative to the probe → ρ

Our proposal

Entire AdS Universe with probe → dual quantum state $|\psi\rangle$

State of the Universe relative to the probe → ρ

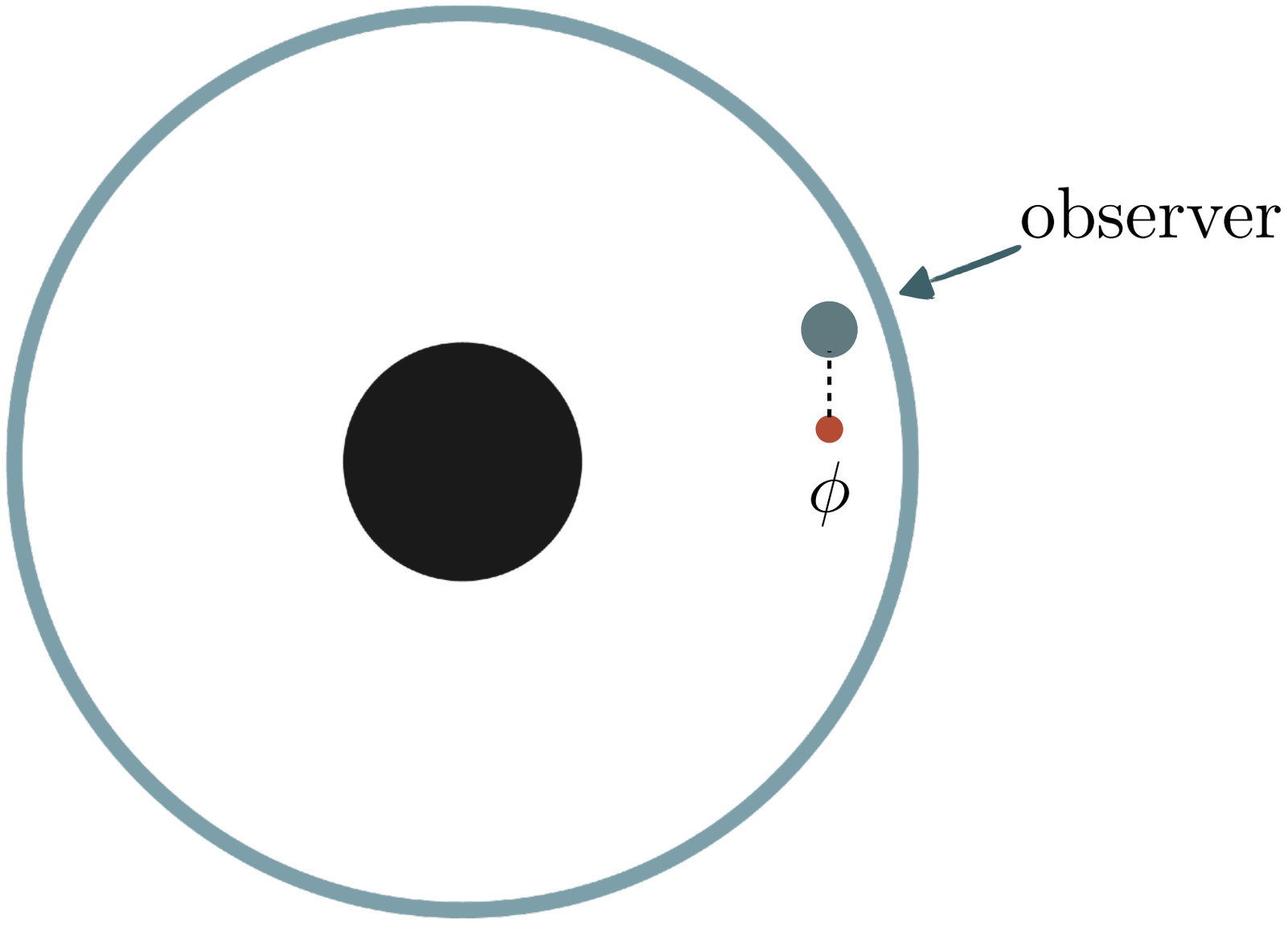
Proper time flow → $\rho^{i\tau}$ (a) near the probe

D.L. Jafferis, **L.L.** 2020

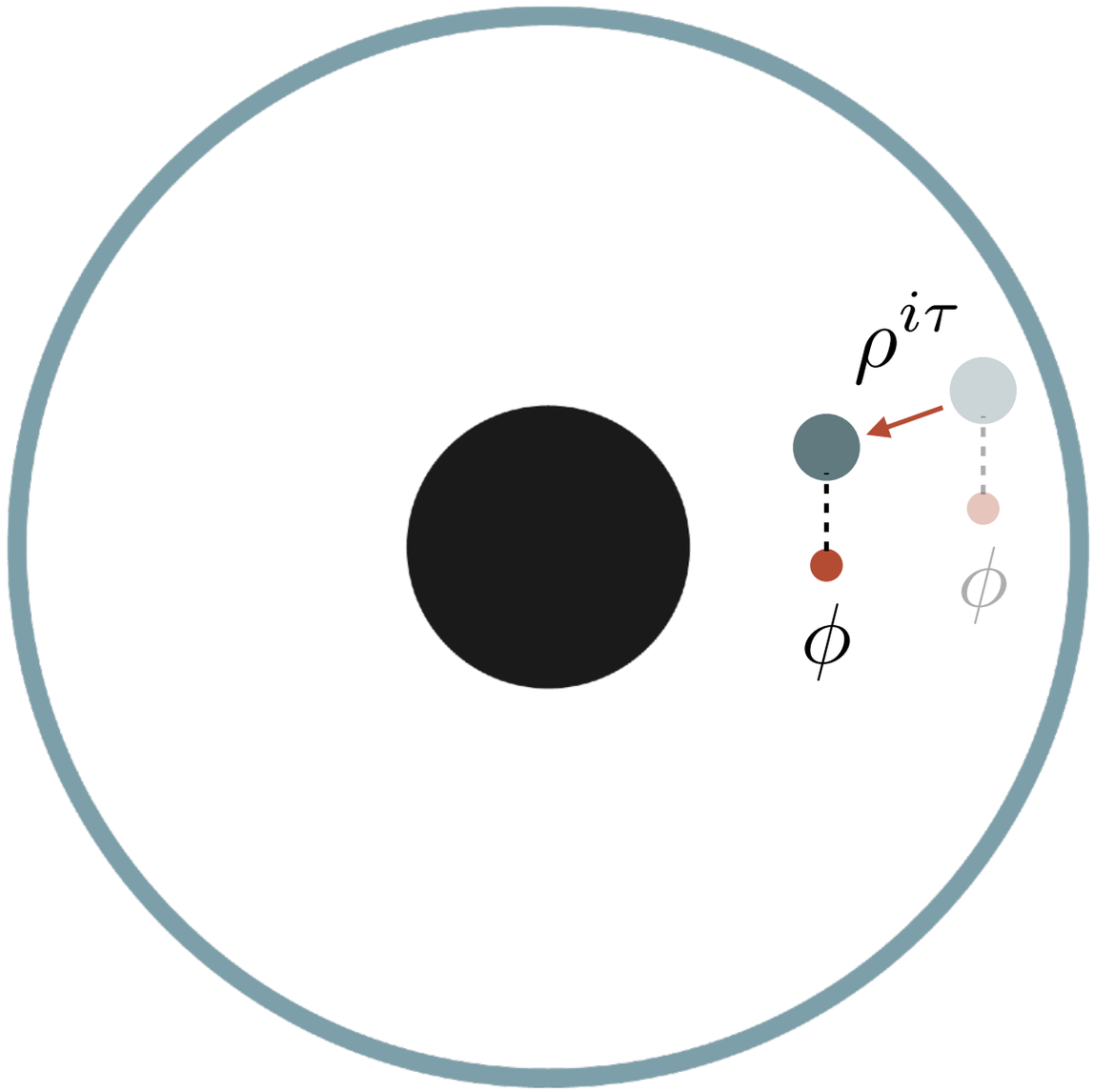
(b) in special states

J. de Boer, D.L. Jafferis, **L.L.** 2021
to appear

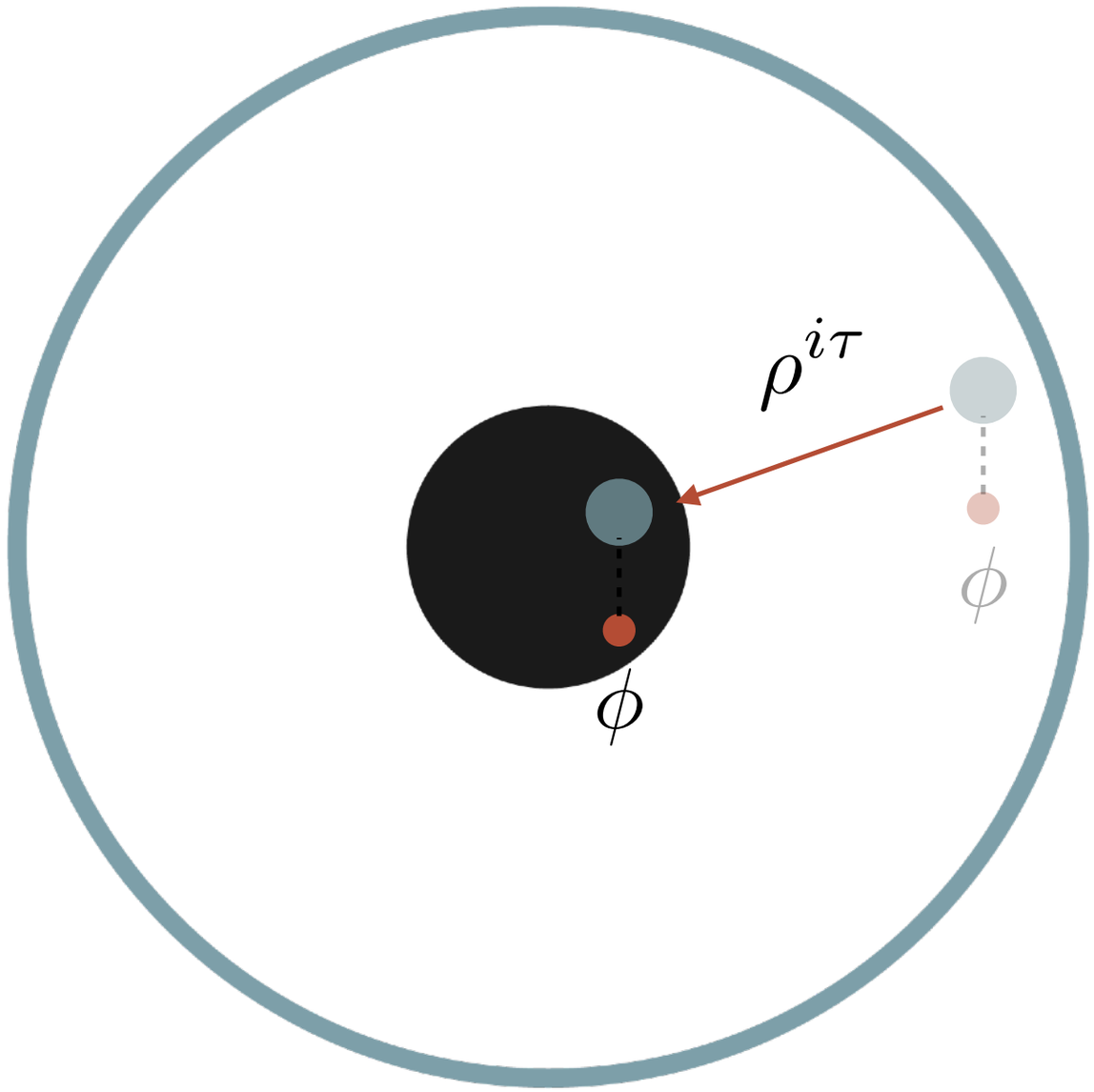
Modular time $=$ Proper time



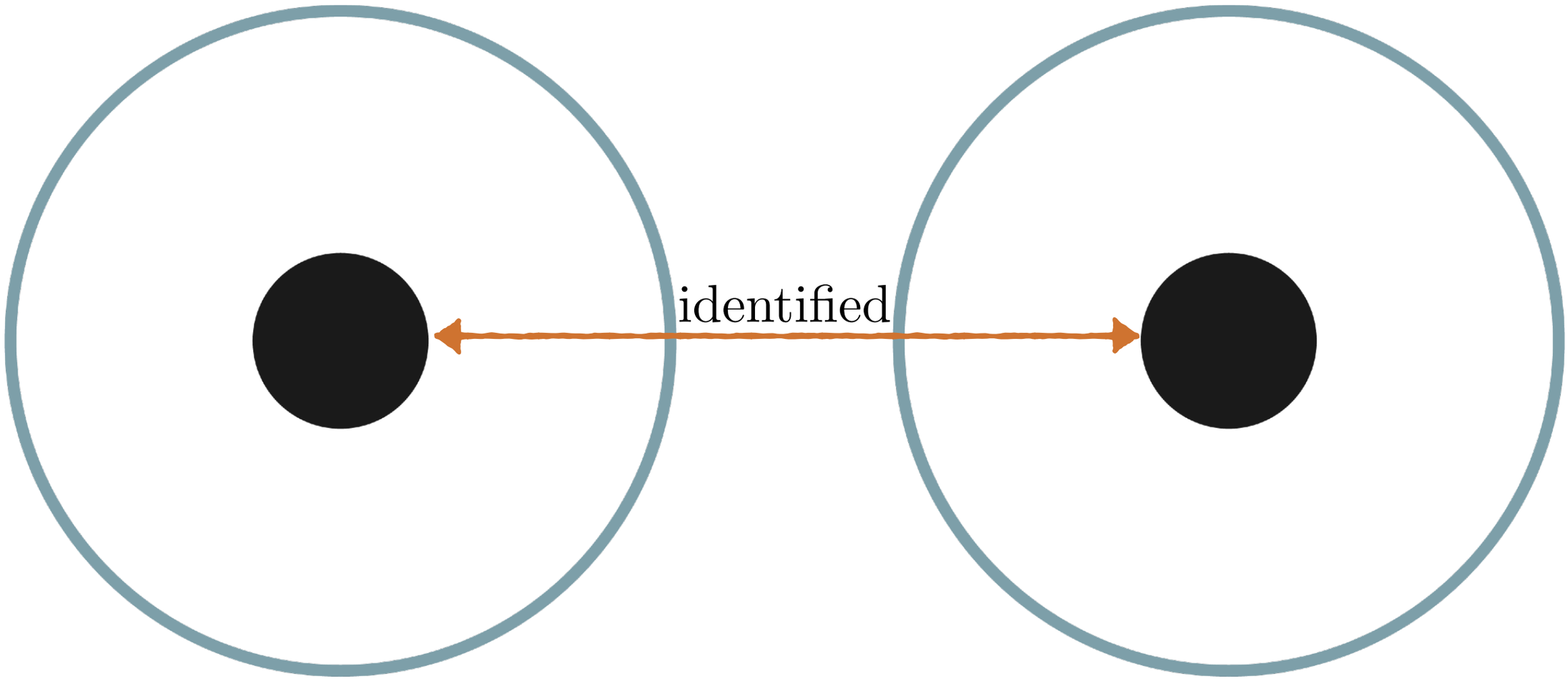
Modular time $=$ Proper time



Modular time $=$ Proper time

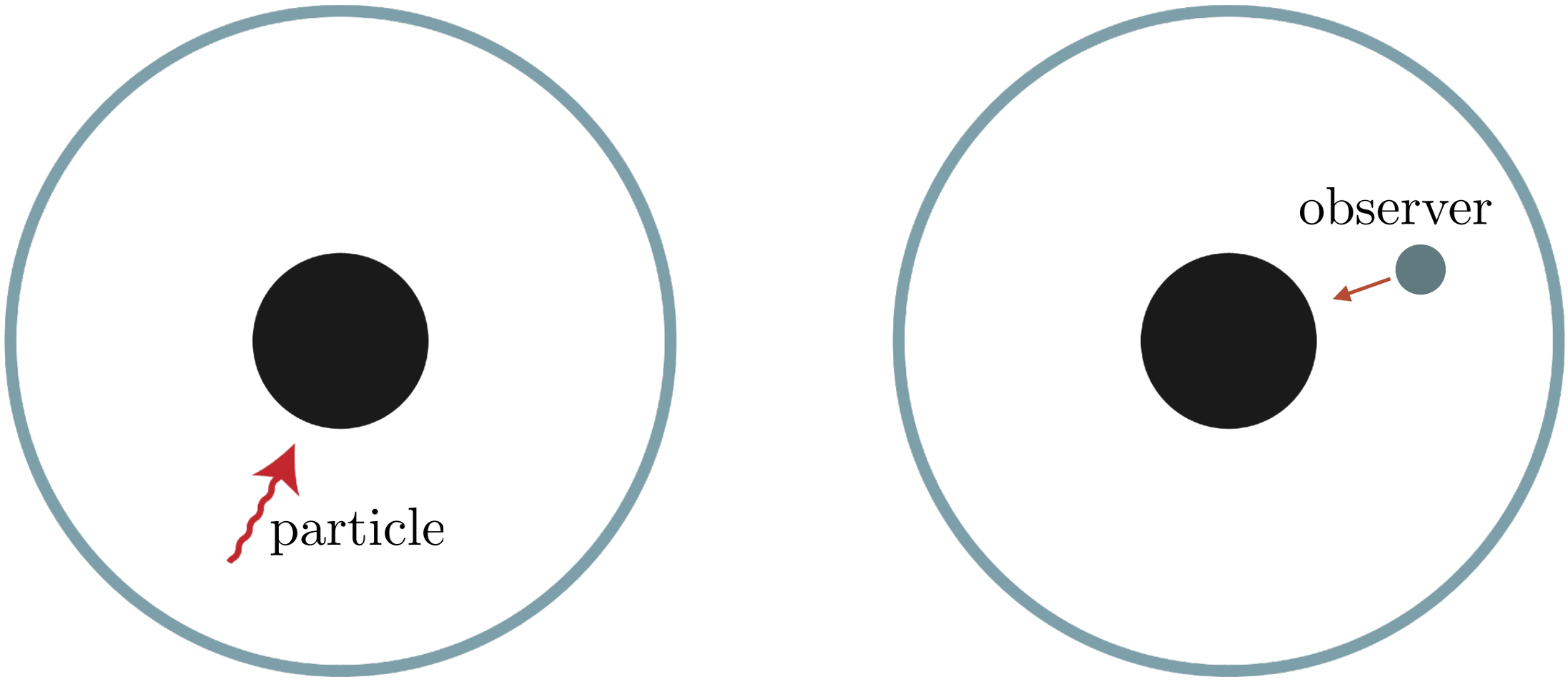


We can see behind "wormhole" horizons!



Einstein-Rosen bridge

We can see behind "wormhole" horizons!



We can detect left signals with observer entering from the right!

SYK/AdS$_2$

Jackiw-Teitelboim

dilaton gravity in AdS$_2$

$$I_{JT} = \int dx^2 \sqrt{g} \Phi \left(R + 2 \right) + I_{\partial B}$$

Pair of SYK models

$$H = H_l + H_r$$

$$H_{l,r} = i^{q/2} \sum J^{l,r}_{j_1 \cdots j_q} \psi^{j_1}_{l,r} \cdots \psi^{j_q}_{l,r}$$

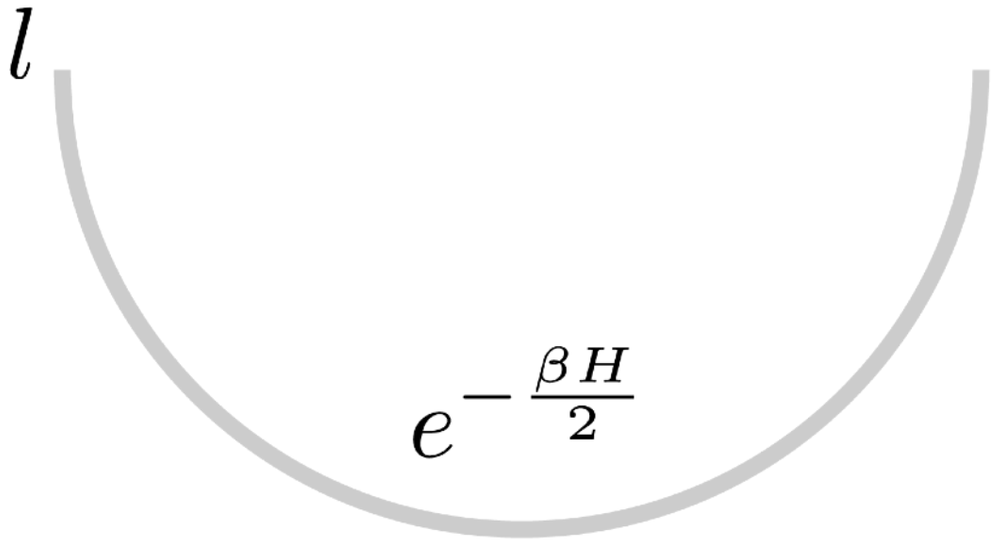
$$\{ \psi^j_a, \psi^k_b \} = \delta_{ab} \delta^{jk}$$

$$j, k = 1, \ldots, N \quad \text{flavors}$$

$$a, b = \text{left}, \text{right}$$

$\mathrm{SYK}/\mathrm{AdS}_2$

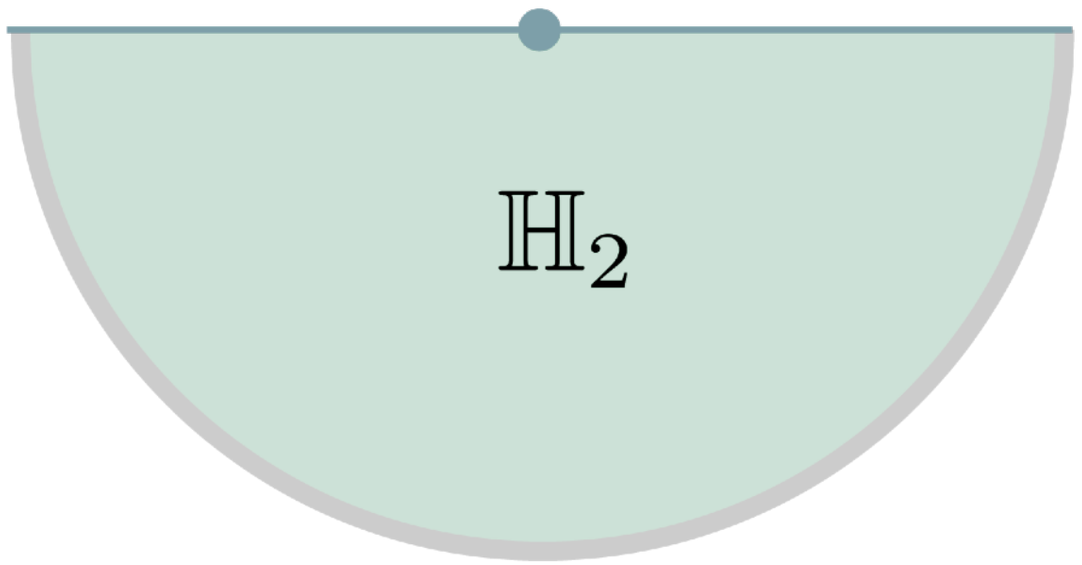
Thermofield double



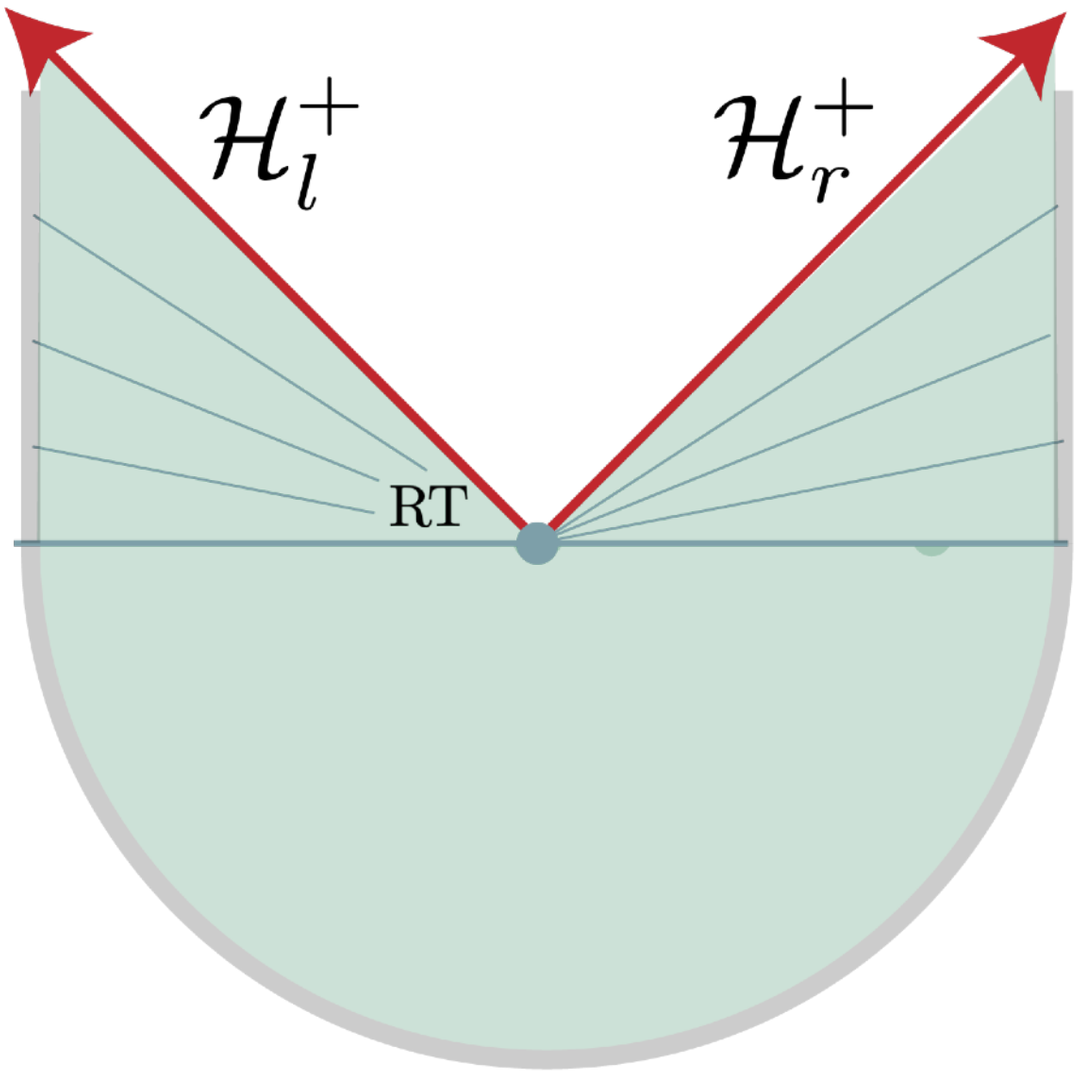
$$|\beta\rangle_{lr} \equiv \mathcal{Z}^{-\frac{1}{2}} \sum_a e^{-\frac{\beta E_a}{2}} |E_a\rangle_r |E_a\rangle_l$$

$$= e^{-\frac{\beta}{2} H_r} |\mathrm{max}\rangle_{lr}$$

Hartle-Hawking

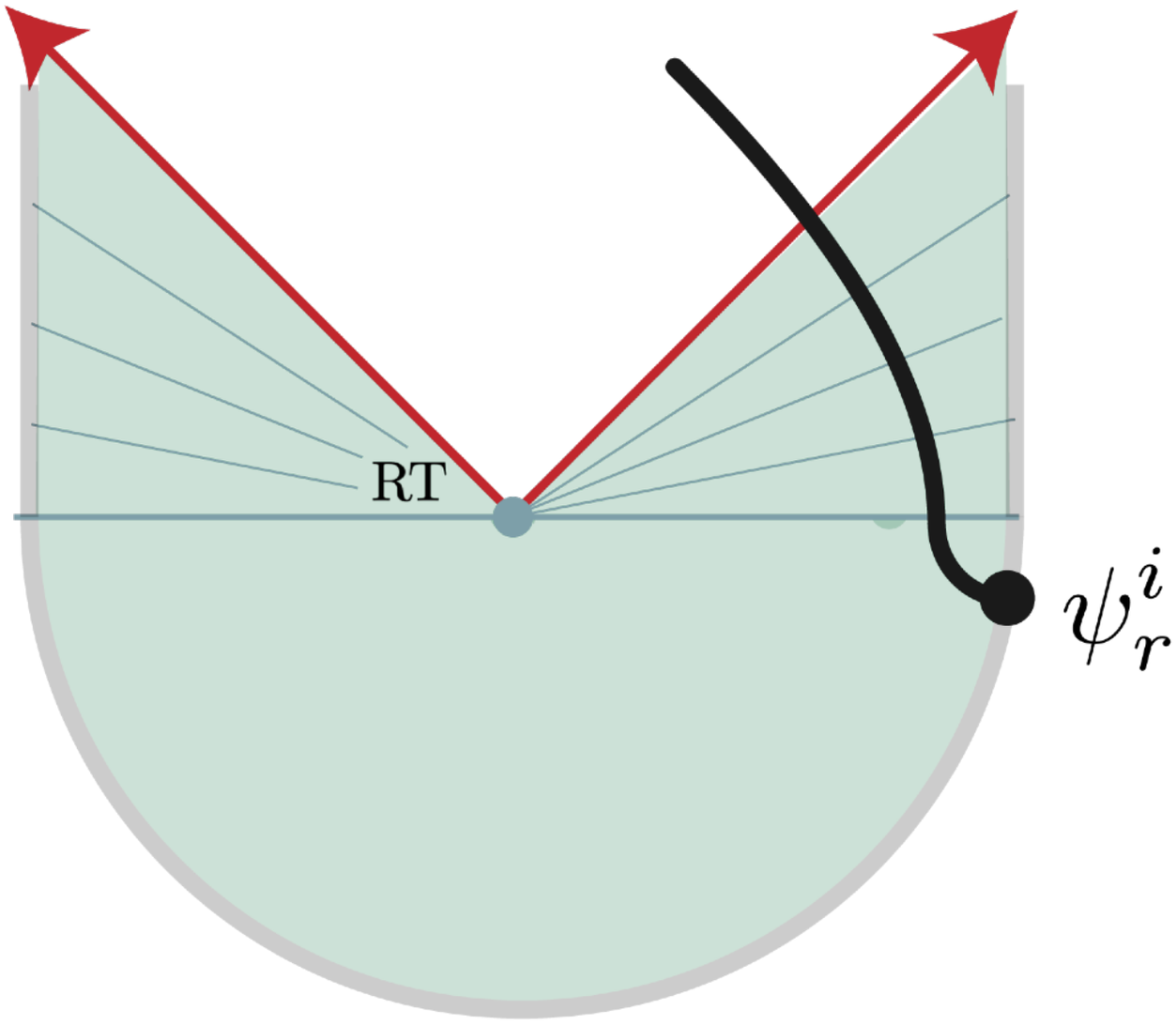


2-sided AdS_2 wormhole



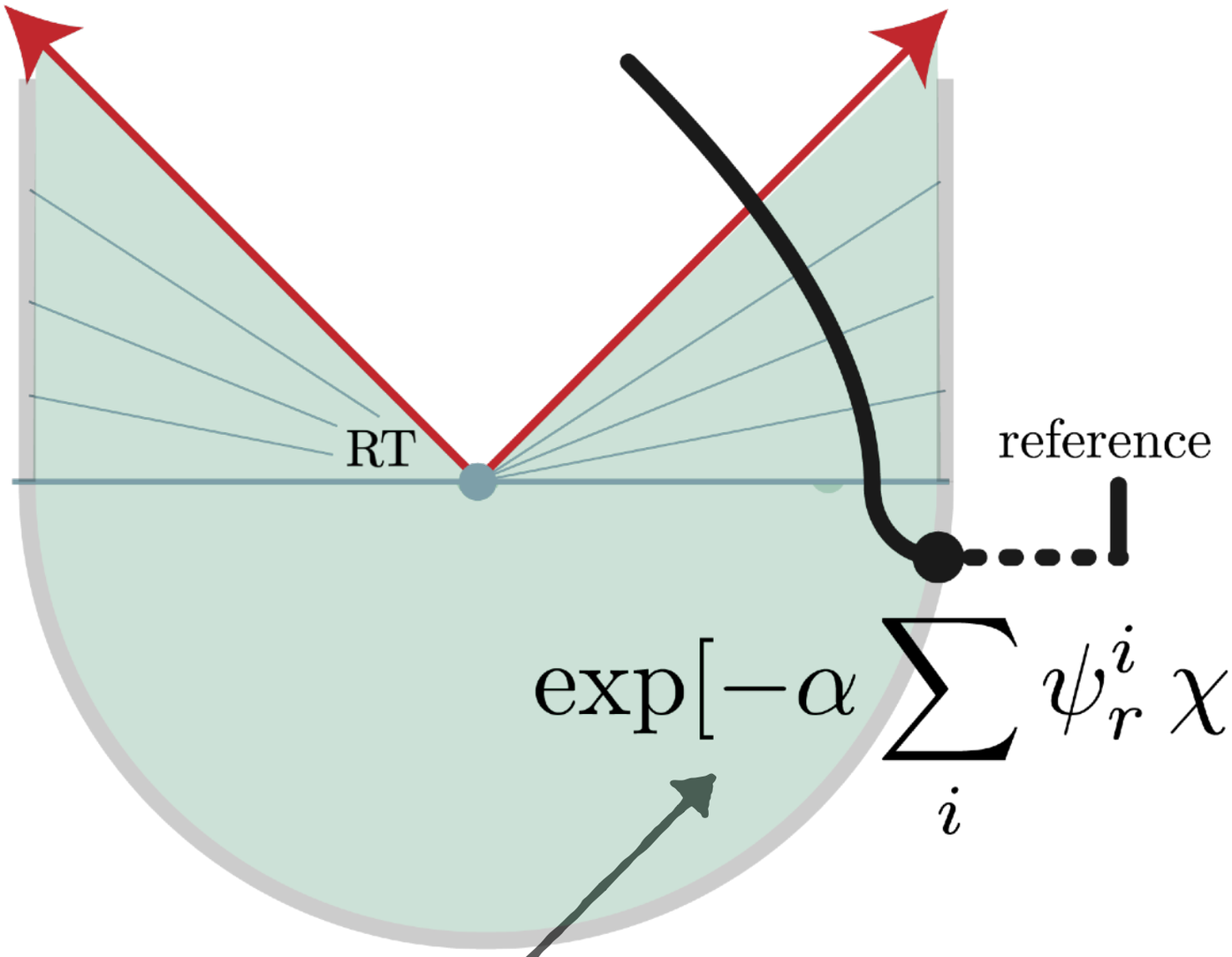
$$|\beta\rangle_{lr} = e^{-\frac{\beta}{2}H_r}|\mathrm{max}\rangle_{lr}$$

Inserting a particle

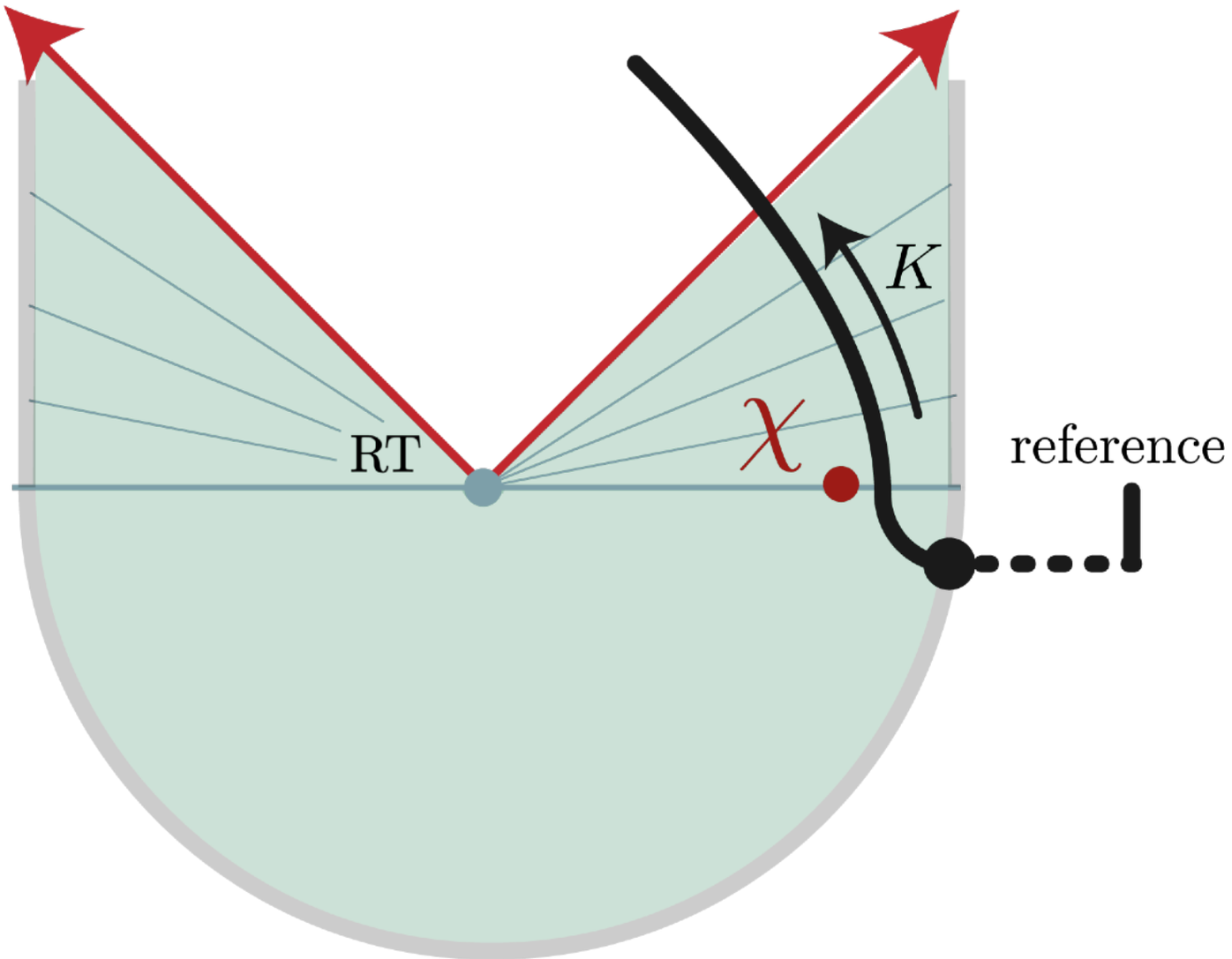


$$e^{-\frac{\beta_l}{2}H_r}\,\psi_r^i\,e^{-\frac{\beta_r}{2}H_r}\big|\max\big\rangle_{rl}$$

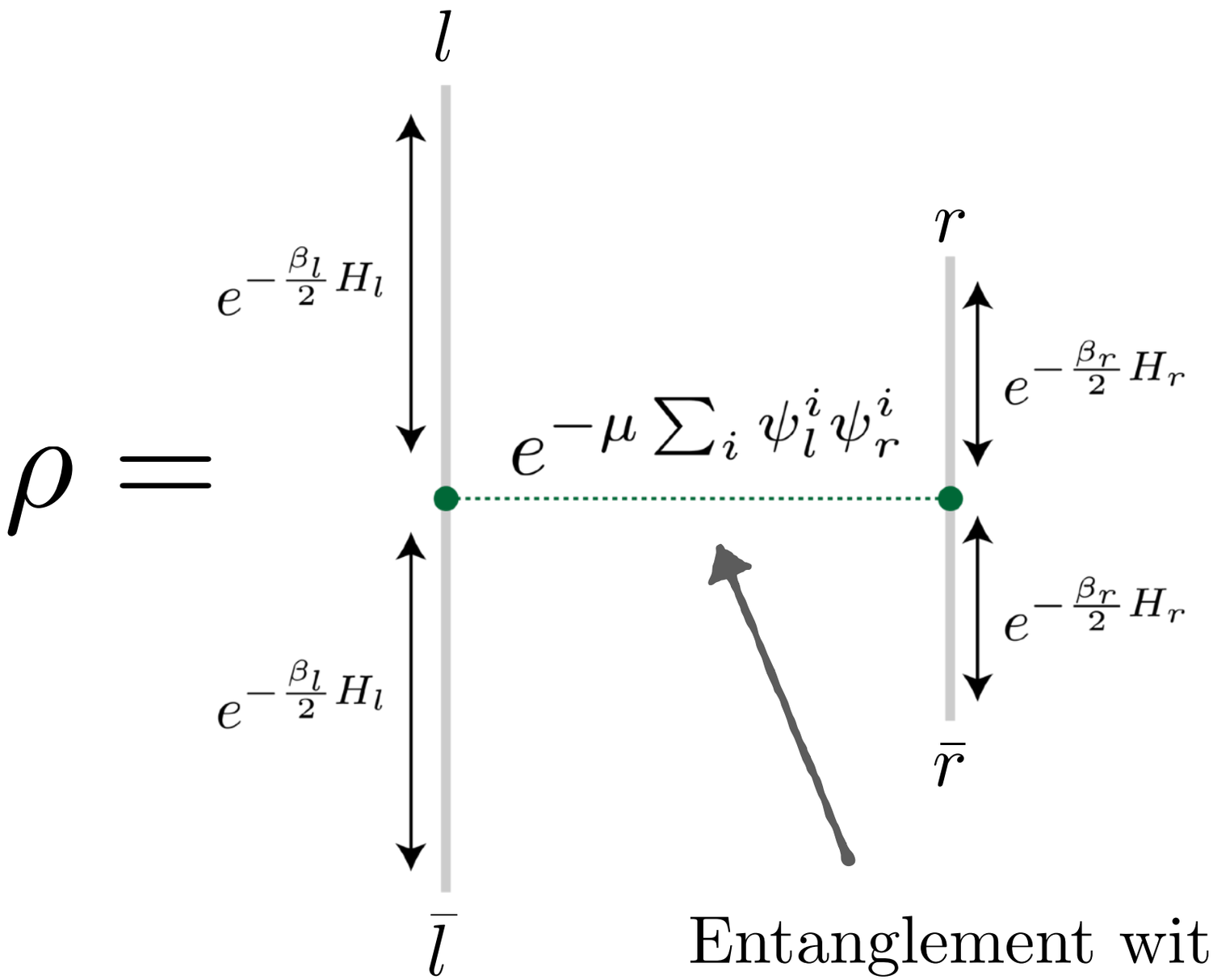
Inserting an observer



Q: How to transport bulk χ along observer's geodesic?



Tracing out the reference



Entanglement with reference

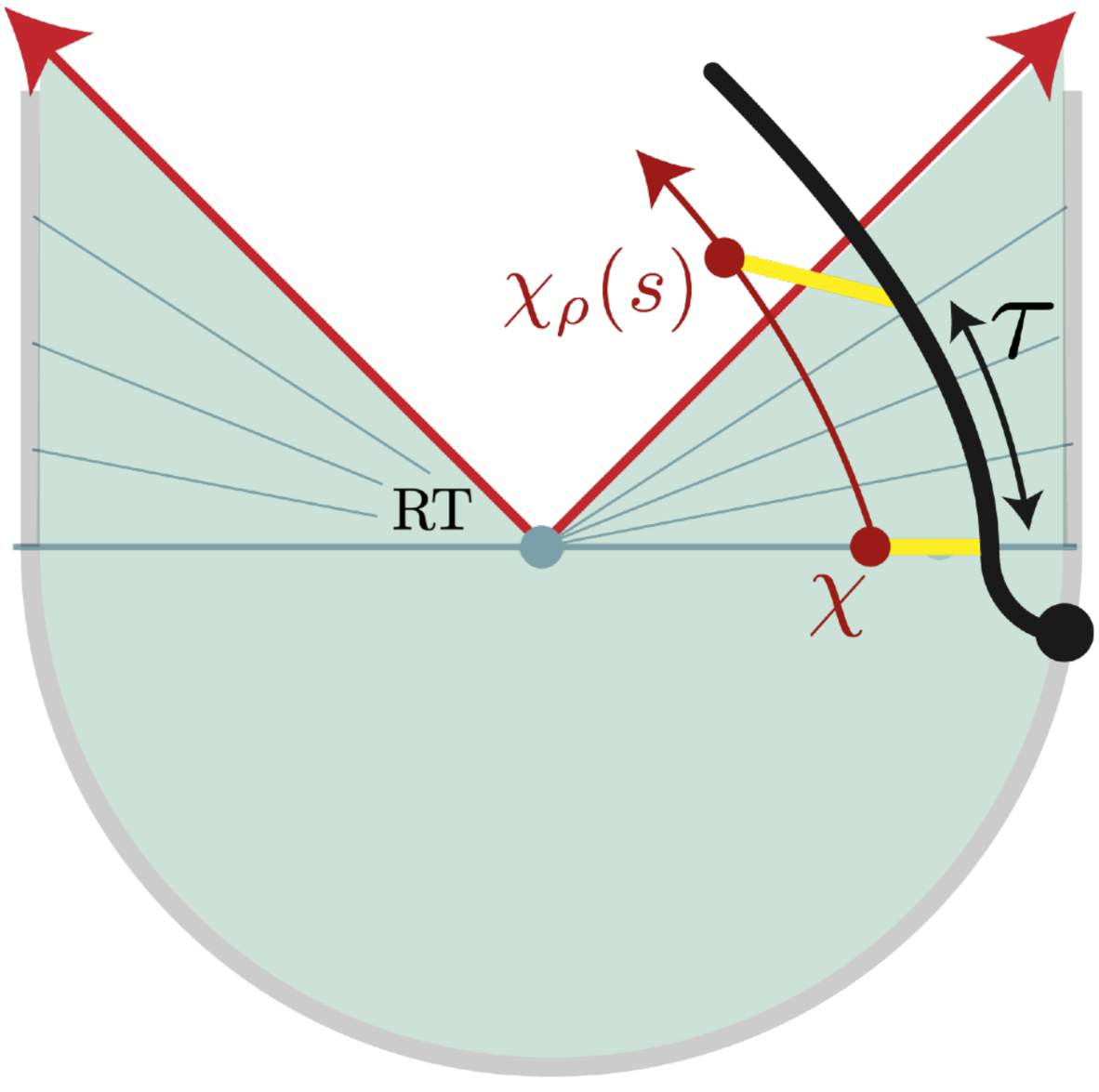
controls l-r coupling

Modular flow

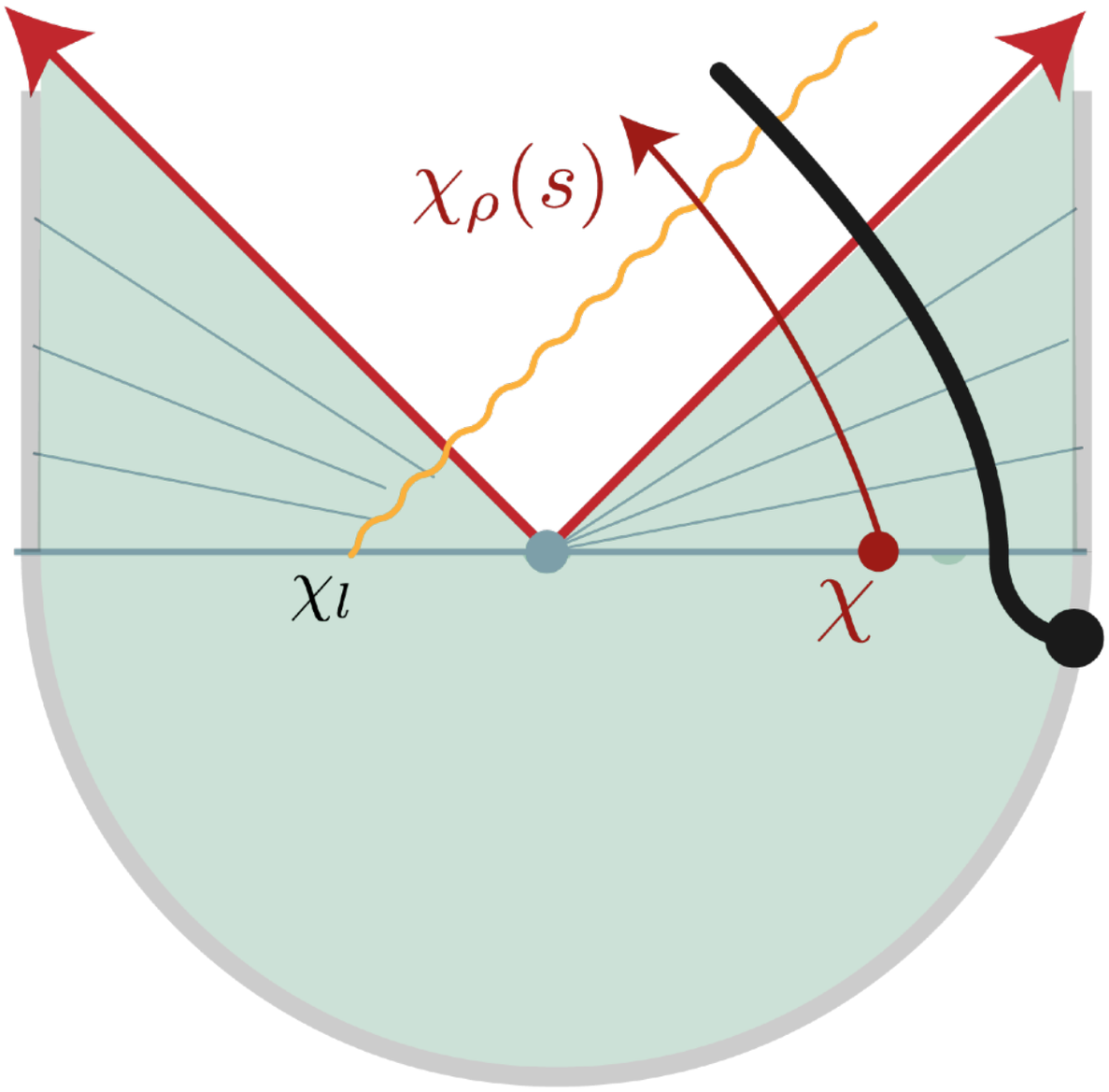
$$\chi_\rho(s) \equiv \rho^{-is}\,\chi\,\rho^{is}$$

Proper time evolution

$$s = \frac{\tau}{\beta_{probe}}$$

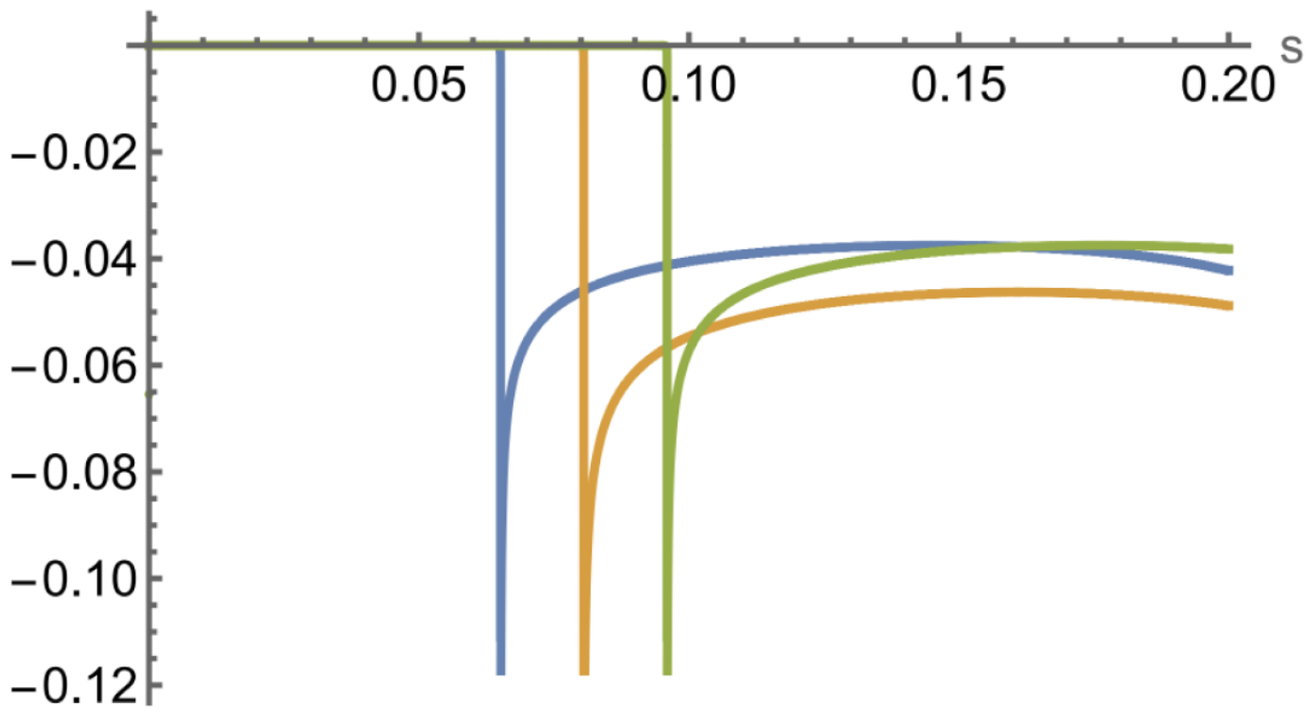


$$W_{lr}(s) = \mathrm{Tr}[\rho\{\chi_\rho(s)\,,\,\chi_l\}]$$



Result of the SYK computation!

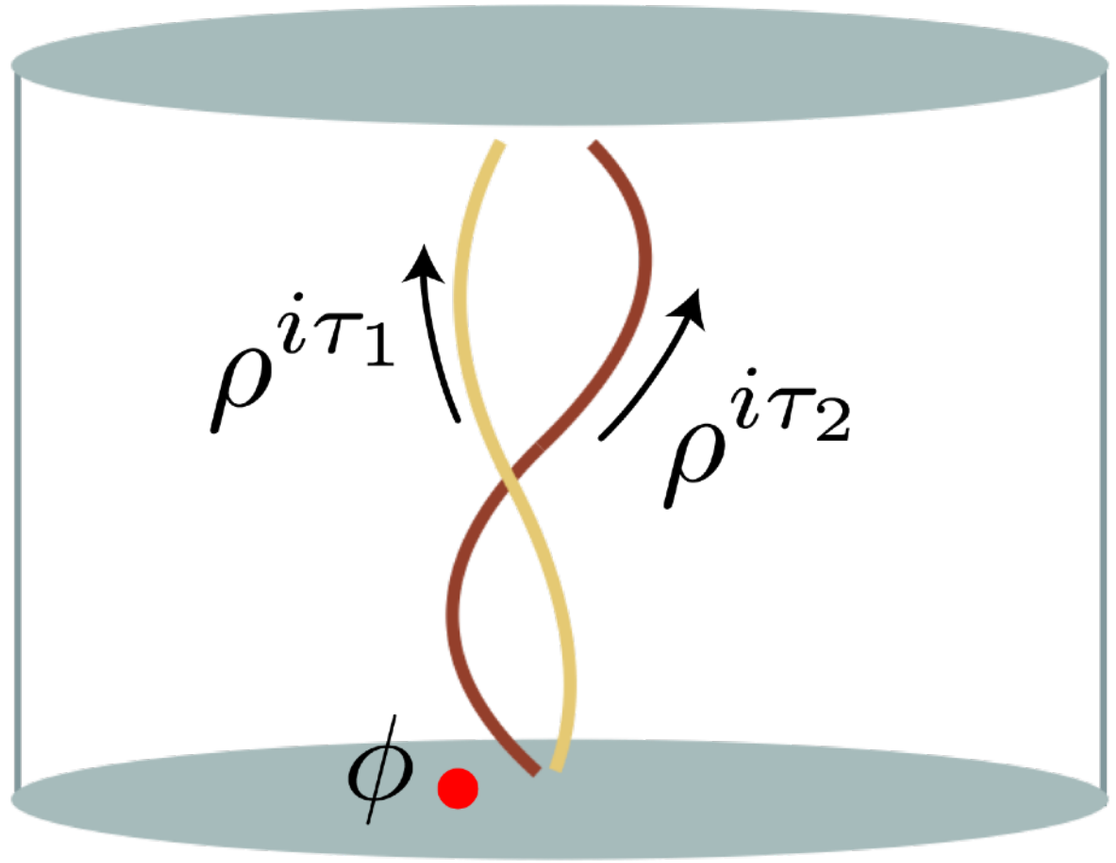
$$W_{lr}(s) = \mathrm{Tr}[\rho\{\chi_\rho(s)\,,\,\chi_l\}]$$



We derive time dilation from quantum mechanics!

Observer "twins" that start and end near each other

$\tau_1 - \tau_2 =$ GR time dilation



Our proposal

Quantum correlations between observer and environment
in Quantum Gravity

↓

origin of observer's proper time

(distinct from dynamical Hamiltonian of boundary system!)

↓

Use it to see inside black holes!

Looking ahead

Does a typical black hole have interior?

Last vestige of information problem in AdS!

A new upcoming era of "experimental"

Quantum Gravity?

AdS universes are dual to quantum systems

Can be simulated on future quantum computers

Perform experiments using internal observers!