OBSERVATIONAL SIGNATURES OF QUANTUM GRAVITY: SEARCHING FOR UV PHYSICS IN THE INFRARED

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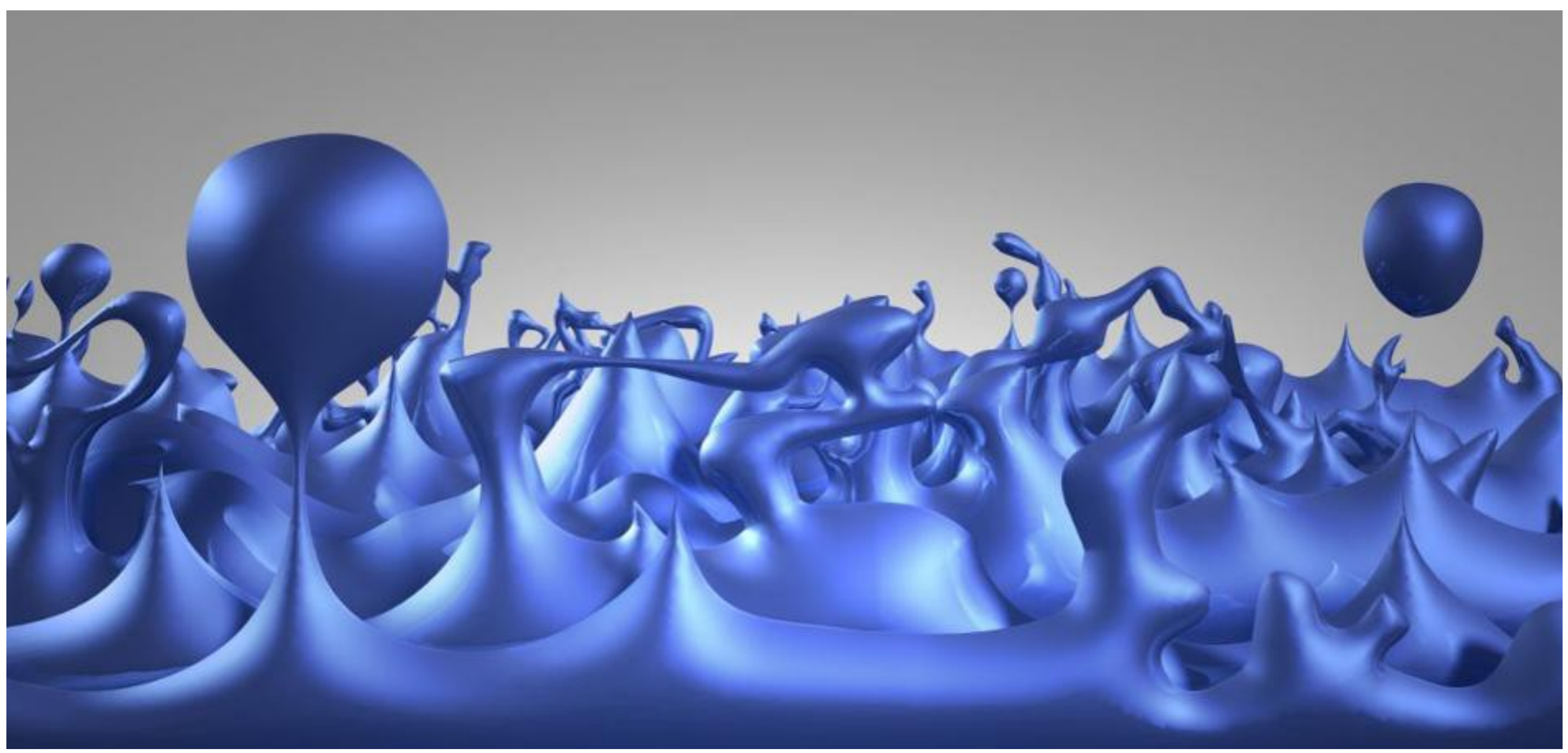
Based on work with:
Verlinde 1902.08207, 1911.02018, in progress
KZ 2012.05870
Banks 2108.04806
Gukov, Lee, 2205.02233
Please see Snowmass whitepaper for summary of this talk, 2205.01799

QUANTUM GRAVITY

—> FLUCTUATIONS IN SPACETIME

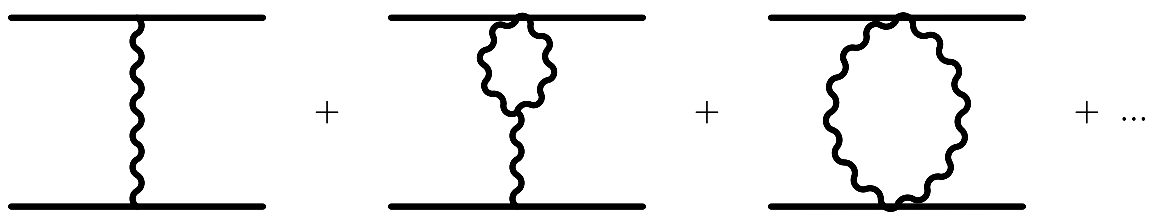
OLD VIEW: VISIBLE ONLY AT ULTRASHORT DISTANCES



$$l_p \sim 10^{-35}\ \mathrm{m} \sim 10^{-43}\ \mathrm{s}$$

PERTURBATIVELY, THERE SHOULD BE NO OBSERVATIONAL EFFECTS

- From usual EFT reasoning: $l_p \sim 10^{-35}\ \mathrm{m} \sim 10^{-43}\ \mathrm{s}$



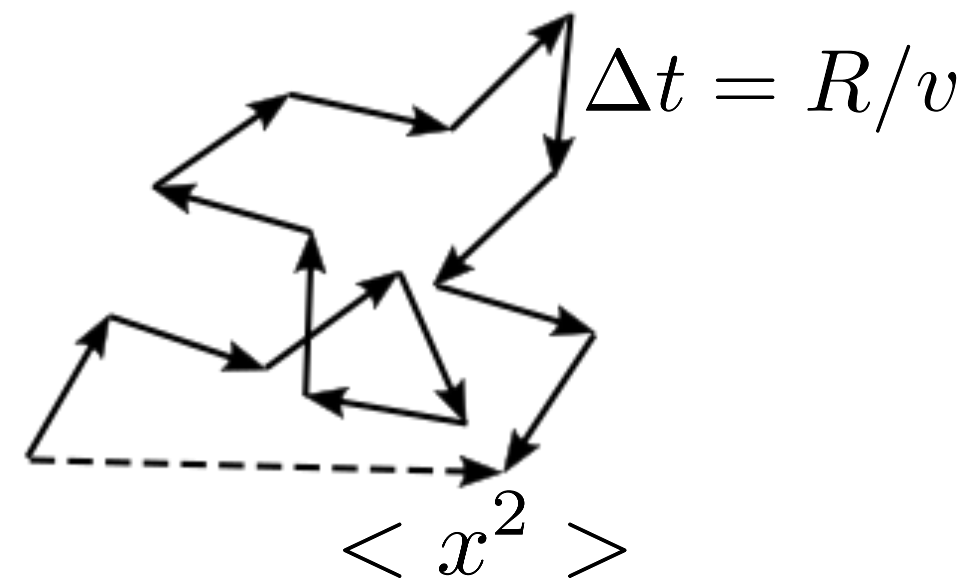
$$V(r) = -\frac{Gm_1m_2}{r}\left(1 + a\frac{G(m_1+m_2)}{rc^2} + b\frac{G\hbar}{r^2c^3}\right)$$

Donoghue, lecture notes on QG as EFT

- G_N is the expansion parameter, and quantum effects enter at l_p^2
- Good reason: effects are naturally at Planckian length scales with Planckian frequencies, for which no experiment exists
- Any observable should be “analytic” in coupling constant G

BROWNIAN NOISE

- UV Effects Can be Transmuted to the Infrared



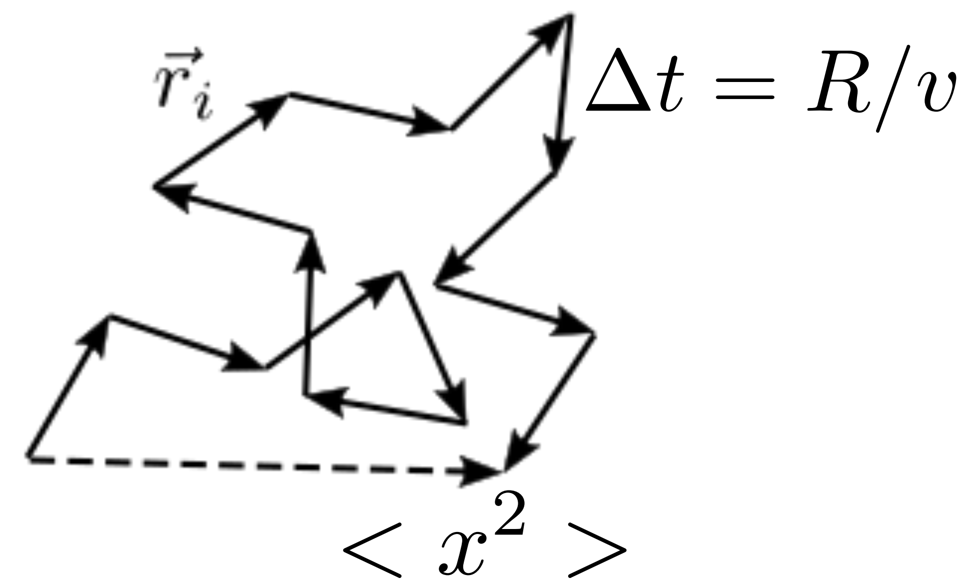
$$\langle x^2 \rangle = 2DT$$

$D \sim \Delta t$ — *Observing time*

UV Scale — *IR Scale*

BROWNIAN NOISE

➤ UV Effects Can be Transmuted to the Infrared



$$\langle x^2 \rangle = 2DT \sim N\Delta t^2$$

N = number of times a typical particle interacts

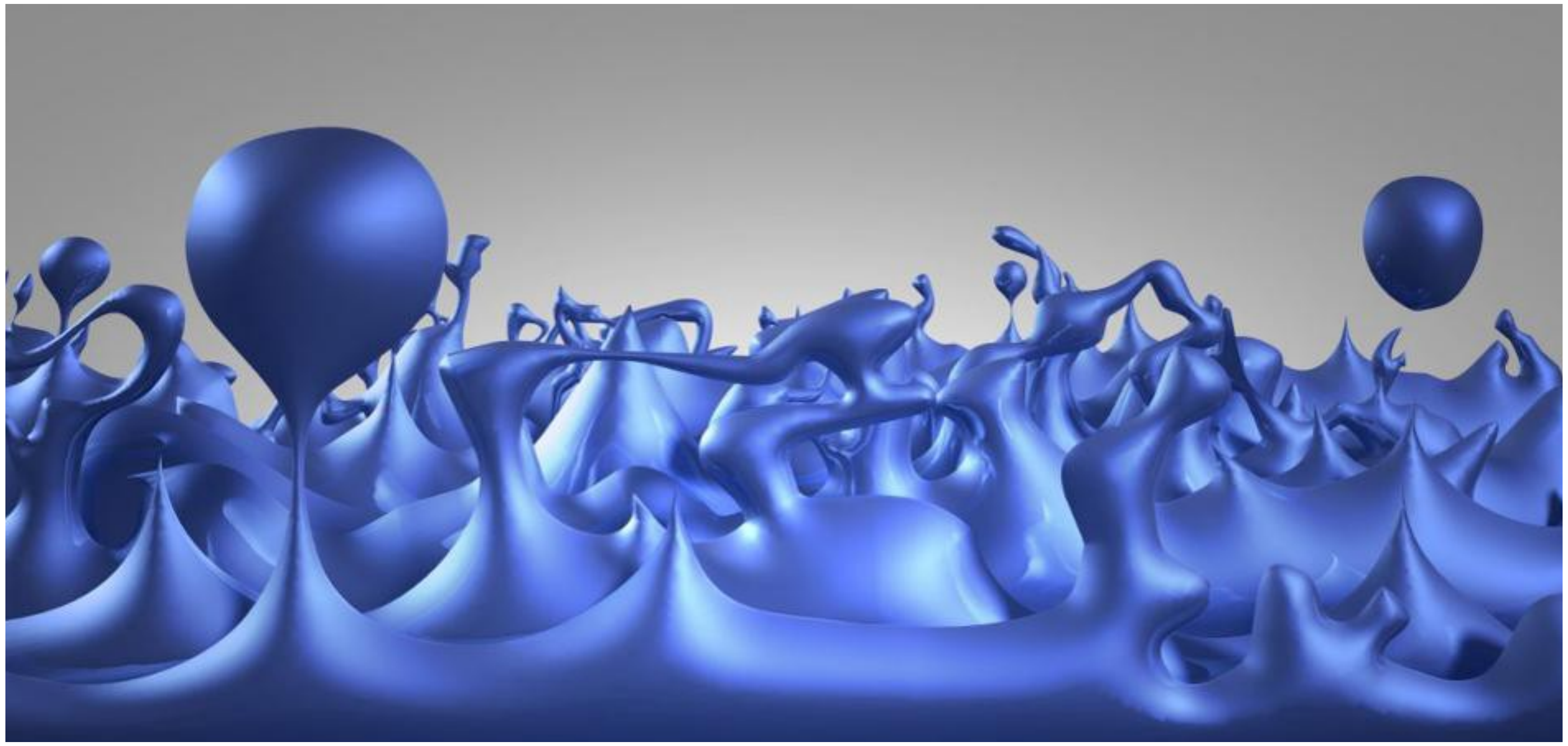
$$N = \frac{T}{\Delta t} \qquad \Delta x \sim \sqrt{N}\Delta t$$

Diffusion is simply "Random walk" or "Root N" statistics

QUANTUM GRAVITY

—> FLUCTUATIONS IN SPACETIME

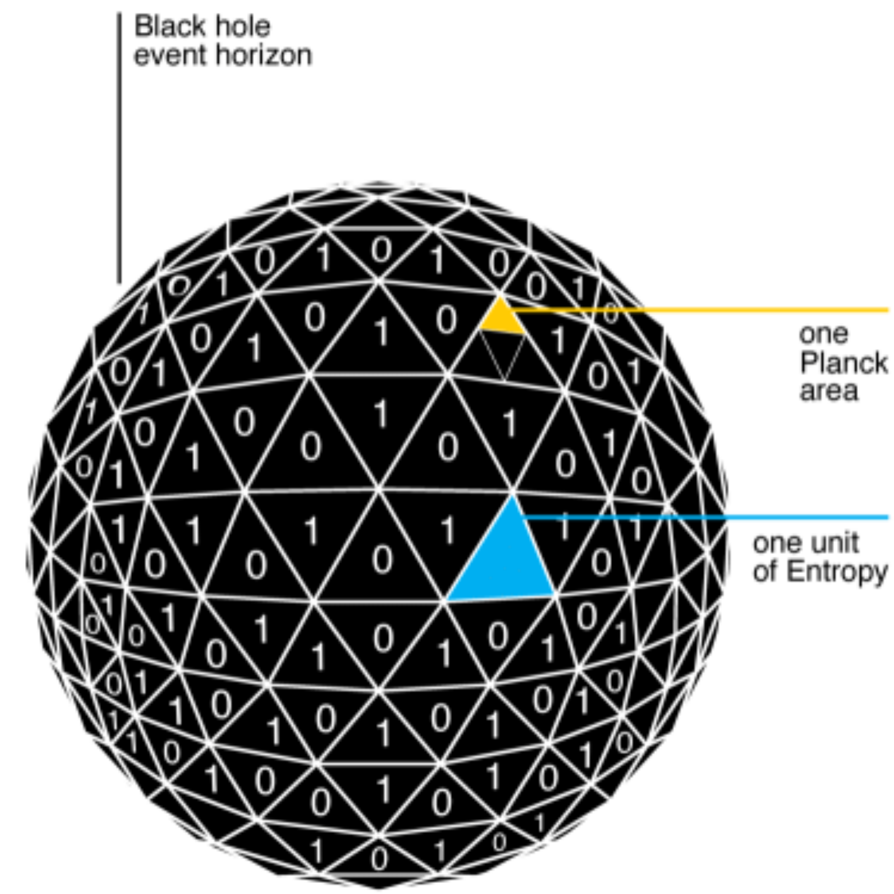
NEW VIEW: INFRARED EFFECTS ARE IMPORTANT



$$l_p \sim 10^{-35}\ \mathrm{m} \sim 10^{-43}\ \mathrm{s}$$

PHYSICS AT THE HORIZON

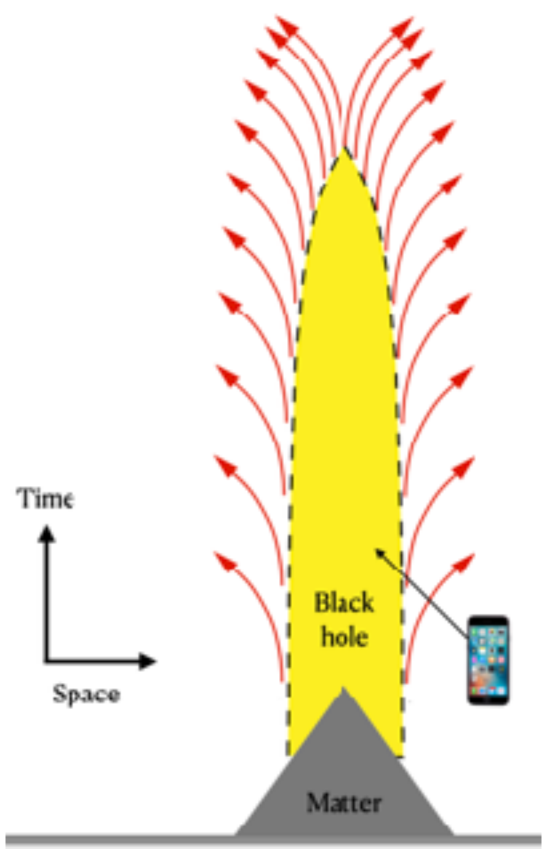
- Physics at horizons enters front and center into holography and QG
- Some naive EFT/ perturbative reasoning breaks down at the horizon
- For example, EFT vastly overcounts degrees-of-freedom of a spacetime volume bounded by surface of area A
- Entanglement between these degrees of freedom — inside and outside horizon — seems to be important



QUANTUM GRAVITY AT BLACK HOLE HORIZONS

NON-LOCALITY AND ENTANGLEMENT PLAY AN IMPORTANT ROLE IN QG

EXAMPLE: PHYSICS AT BLACK HOLE HORIZONS



What happens to the information?

Can't escape, by locality

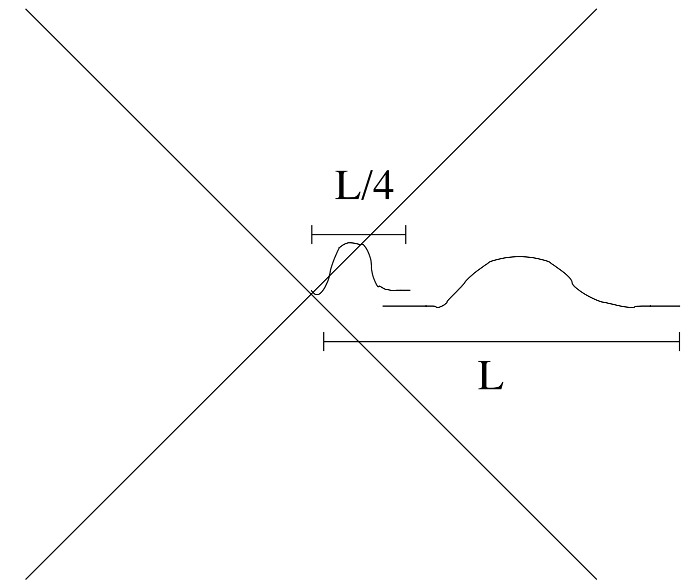
Can't be destroyed, by unitarity

Problem seems to occur at the horizon, where semiclassical gravity should work fine

THE QUANTUM WIDTH OF A (BH) HORIZON

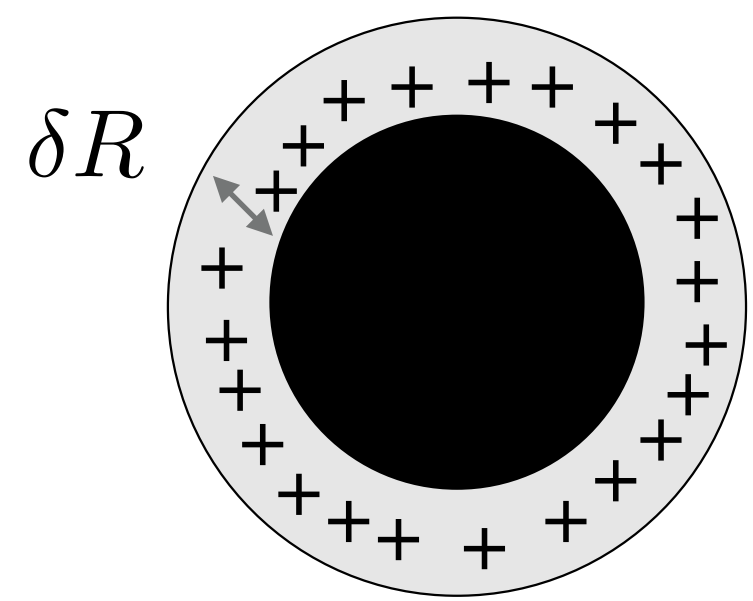
- Degrees-of-freedom ("pixels") can fluctuate

$$\delta R \underset{d=4}{\sim} \sqrt{l_p R}$$



In any number of dimensions:

$$\delta R^2 \sim \frac{R^2}{\sqrt{S_{\mathrm{BH}}}}$$



Marolf 2003

HORIZONS AND EXPERIMENTS

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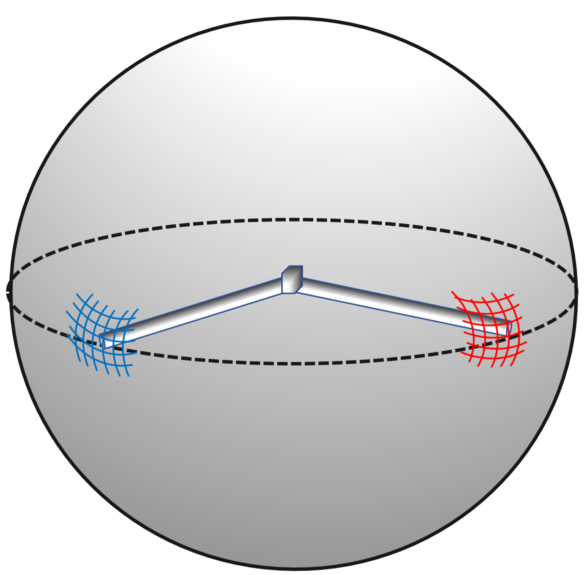
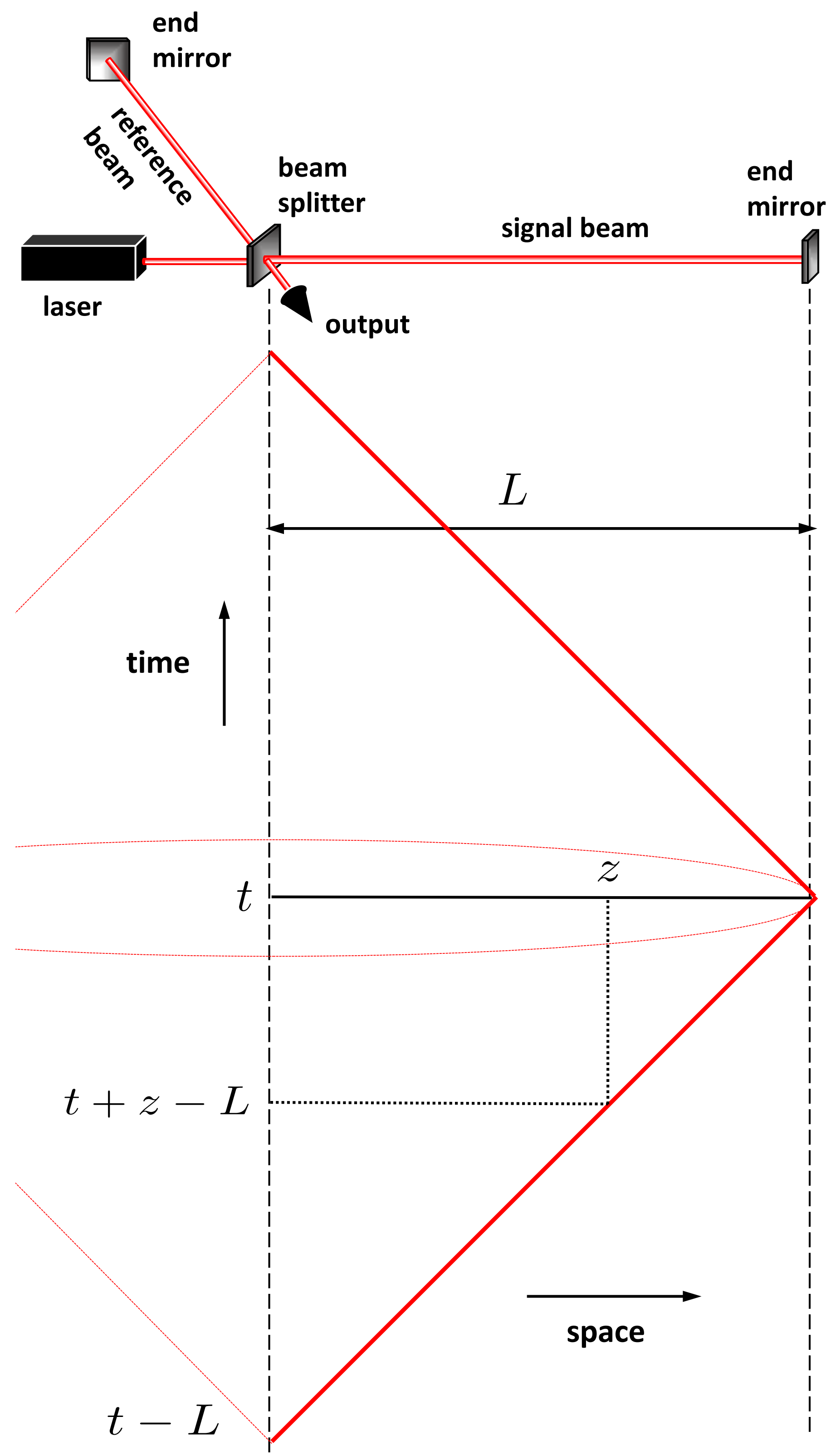
- An experimental measurement defines a horizon
- Consider light beams of an interferometer

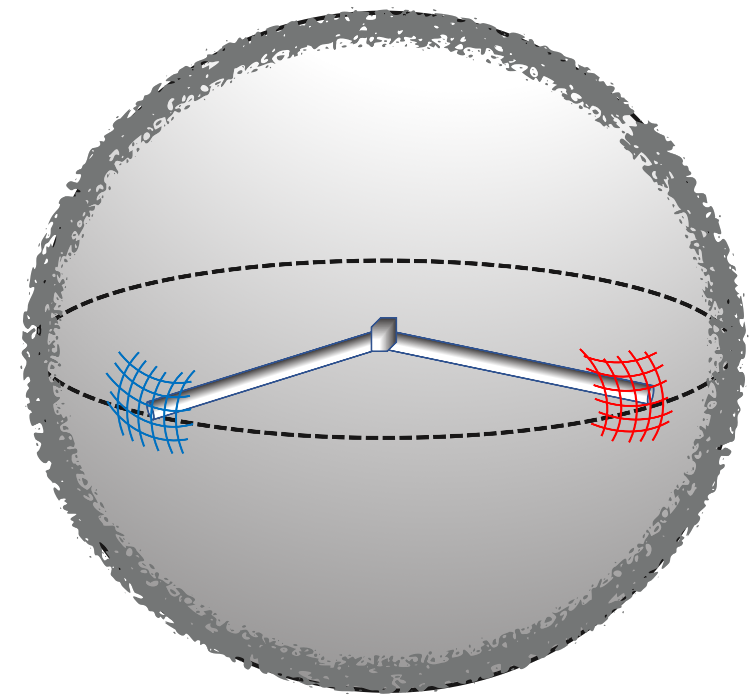




- *Traces out a causal diamond*

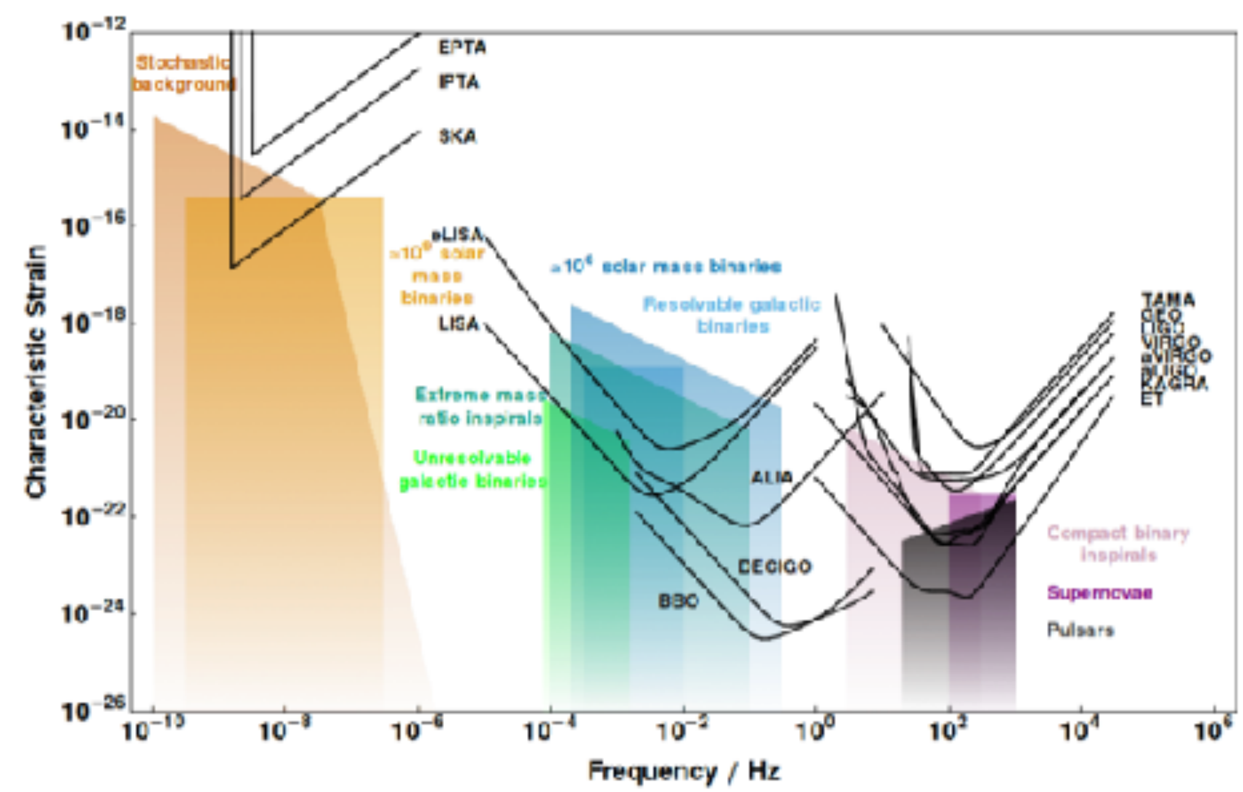
WHAT LENGTH FLUCTUATION CAN BE MEASURED?

$$\delta L(t) = \frac{1}{2}\int_0^L dz\, h(t+z-L)$$



Modern Interferometer Set-Up:

- Strain $\sim \dfrac{\delta L}{L} \sim 10^{-20}$



$$\delta L \sim \sqrt{l_p L}$$

BLACK HOLE – (EMPTY!) CAUSAL DIAMOND DICTIONARY

Black Hole	*Causal Diamond*
➤ Horizon	➤ Horizon Defined by Null Rays
➤ Black Hole Temperature	➤ Size of Causal Diamond $$T \sim 1/L$$
➤ Black Hole Mass	➤ Modular Fluctuation $$M = \frac{1}{2\pi L}\Big(K - \langle K \rangle\Big)$$
➤ Thermodynamic free energy	➤ Partition Function $$F = -\frac{1}{\beta}\log\,\mathrm{tr}\left(e^{-\beta K}\right)$$
➤ Entropy	➤ Entanglement Entropy $$S = \langle K \rangle = \frac{A}{4G}$$

BLACK HOLES VS. FLAT EMPTY SPACE

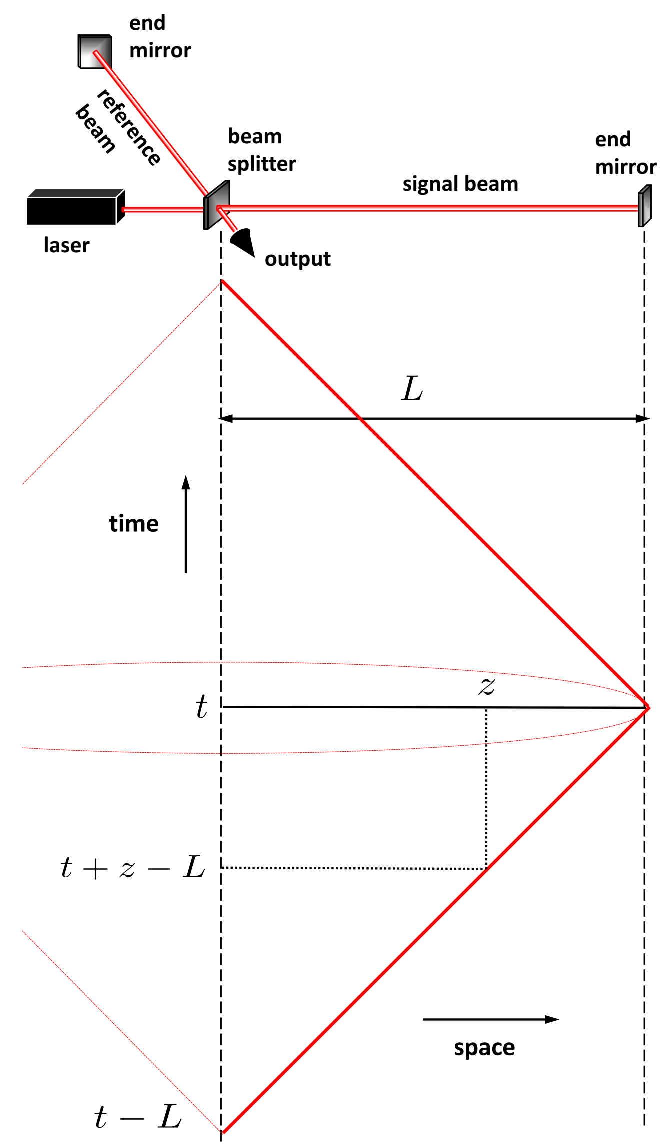
E. Verlinde, KZ 1902.08207
E. Verlinde, KZ 1911.02018

- As long as we are interested in only the part of spacetime inside the causal diamond, the metric in some common spacetimes can be mapped to "topological black hole"

$$ds^2 = dudv + dy^2$$

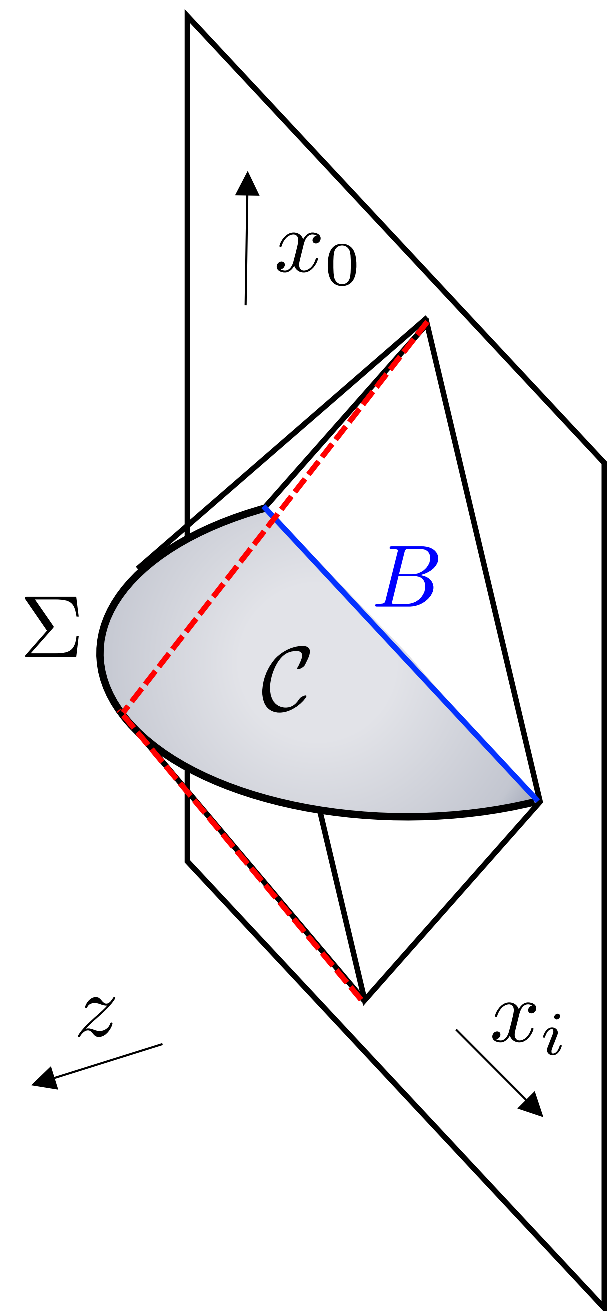
$$ds^2 = -f(R)dT^2 + \frac{dR^2}{f(R)} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$f(R) = 1 - \frac{R}{L} + 2\Phi$$



EVIDENCE FOR THE DICTIONARY — EVEN REGIONS OF VACUUM HAVE AN ENTROPY

- That Entropy describes properties of the vacuum — including its energy fluctuations!
- In any QFT, tracing out the complement region produces a thermal density matrix; in the case of CFT with gravitational dual, thermal and entanglement entropy satisfy area law (Ryu-Takayanagi; Casini, Huerta, Myers)
- Entanglement entropy in QM (Srednicki '98)
- Geometric entropy with Euclidean methods (Callan, Wilczek '95, Cooperman, Luty)



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OUR ARGUMENT (2 STEPS)

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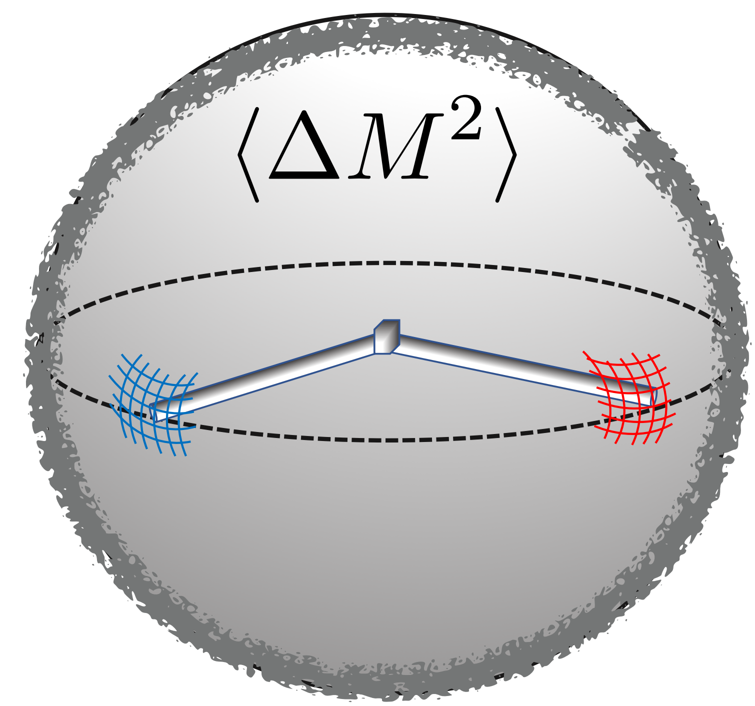
1. Calculate fluctuations in the energy of the vacuum
    A. In AdS/CFT this can be calculated with no assumptions.
    B. In Minkowski space, *we have made a case that the same relations hold*. *Banks, KZ 2108.04806*
        A. Interferometer on flat RS brane
        B. Dimensional reduction of flat E-H action to dilaton gravity a la Solodukhin
2. Calculate length fluctuation from vacuum energy fluctuation $\delta L \sim \sqrt{l_p L}$



1) CALCULATE VACUUM FLUCTUATION

- Number of holographic degrees of freedom is the entropy

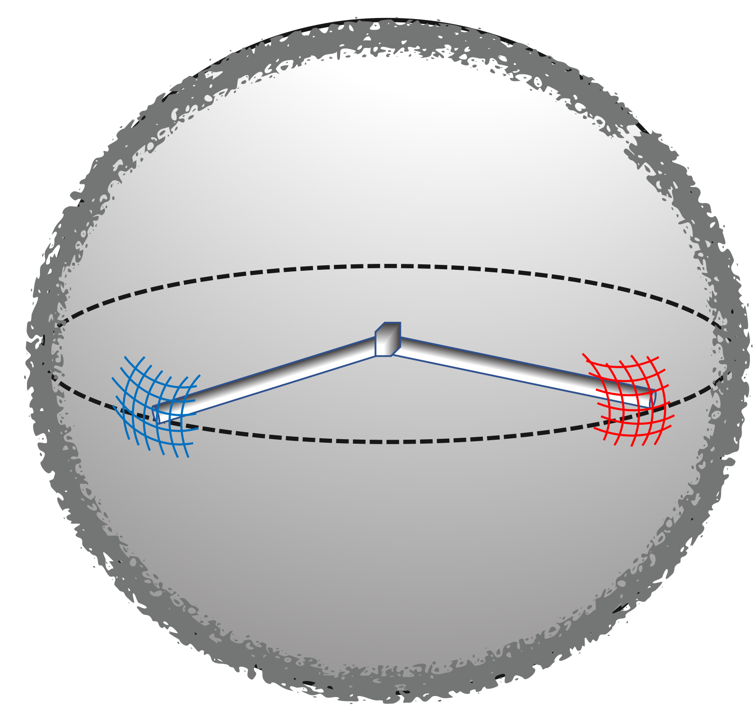
$$S = \frac{A}{4G_N} = \frac{8\pi^2 R^2}{l_p^2}$$

- Each d.o.f. has temperature set by size of volume

$$T = \frac{1}{4\pi R}$$

- Statistical argument:

$$\Delta M \sim \sqrt{S}T = \frac{1}{\sqrt{2}l_p}$$



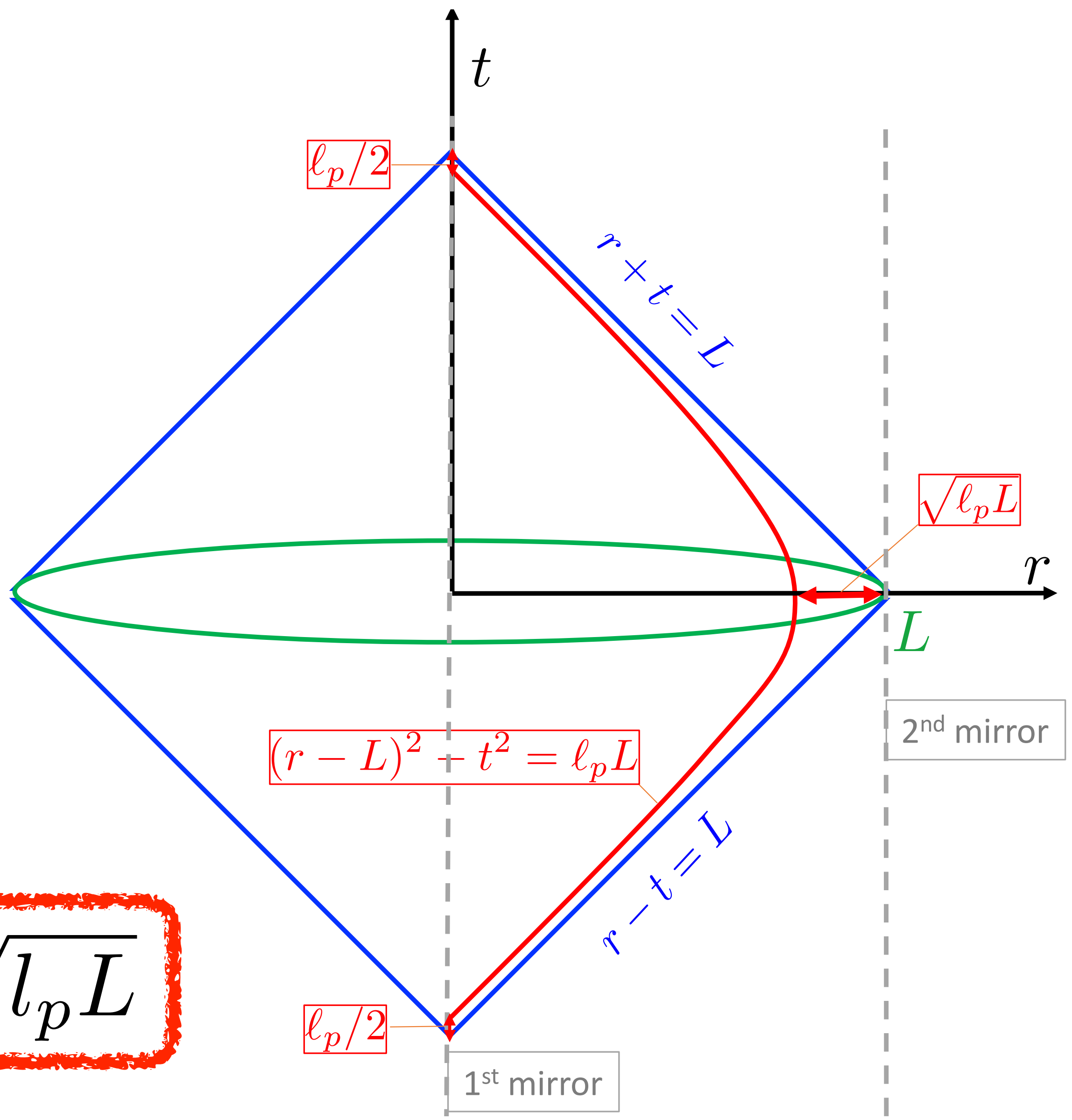
2) VACUUM FLUCTUATION SOURCES METRIC FLUCTUATION

$$\Phi(L) = -\frac{l_p^2 \Delta M}{8\pi L}$$

$$\Rightarrow \quad \Phi \sim \frac{l_p}{L}$$

$$\Phi \sim h_{uu} h_{vv} \sim \frac{\delta L^2}{L^2}$$

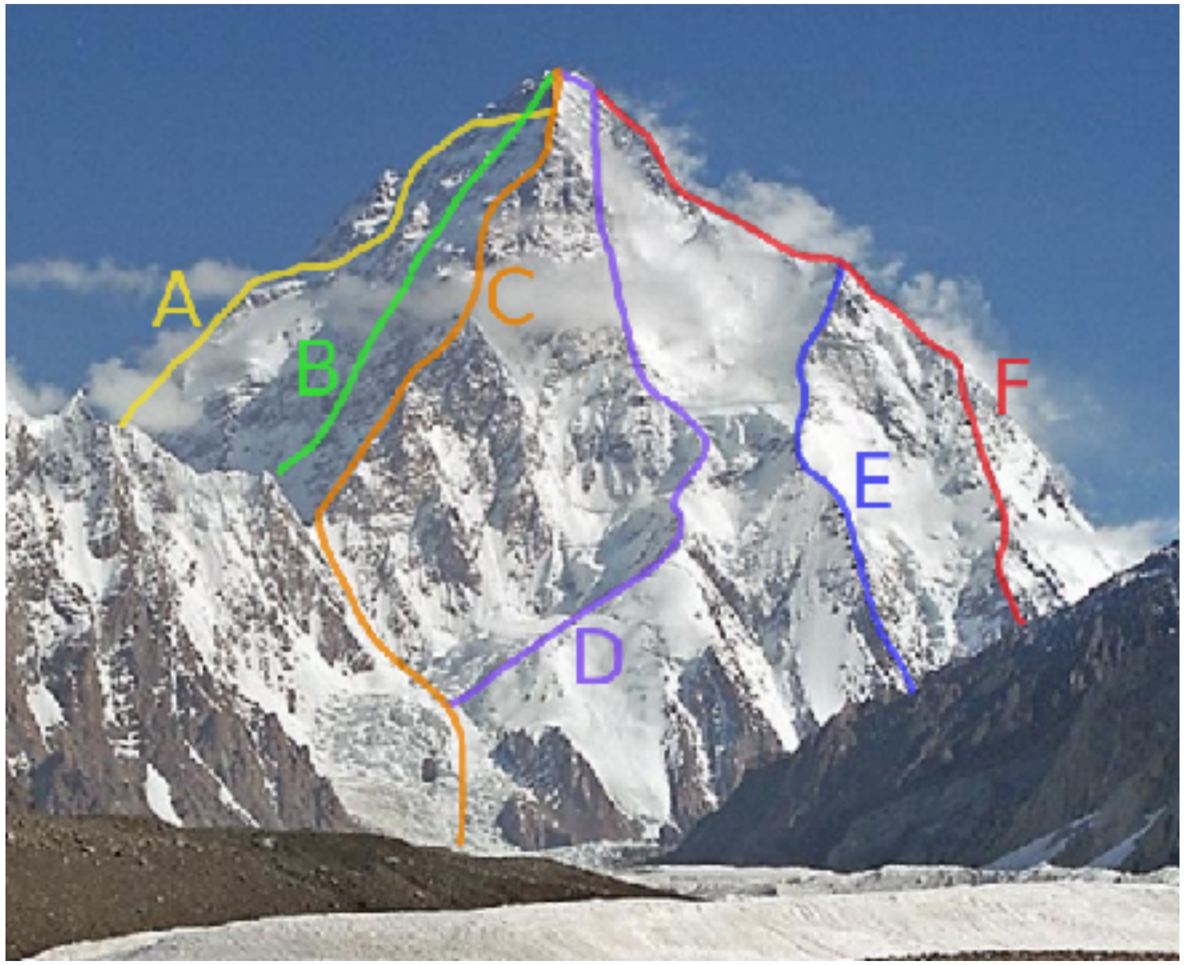
$$\Rightarrow \quad \delta L \sim \sqrt{l_p L}$$



ONE MOUNTAIN, MANY FACES

F. 2-d Models, e.g. JT gravity

A. AdS/CFT



E. Hydrodynamics EFT

B. Light Ray Operators

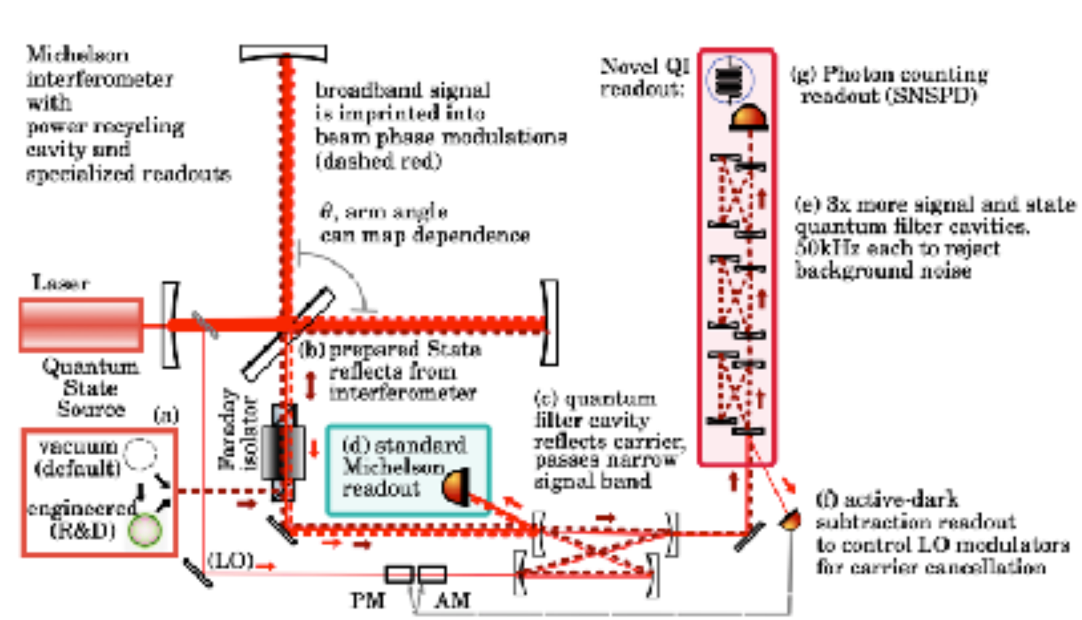
D. TOCs/OTOCs

C. Gravitational effective action / saddle point expansion

EXPERIMENT — GQUEST

- Gravity from the Quantum Entanglement of SpaceTime
- Theory is predictive: amplitude and angular correlations; power spectral density

$$\frac{\delta L^2}{L^2} = \frac{l_p}{4\pi L}$$



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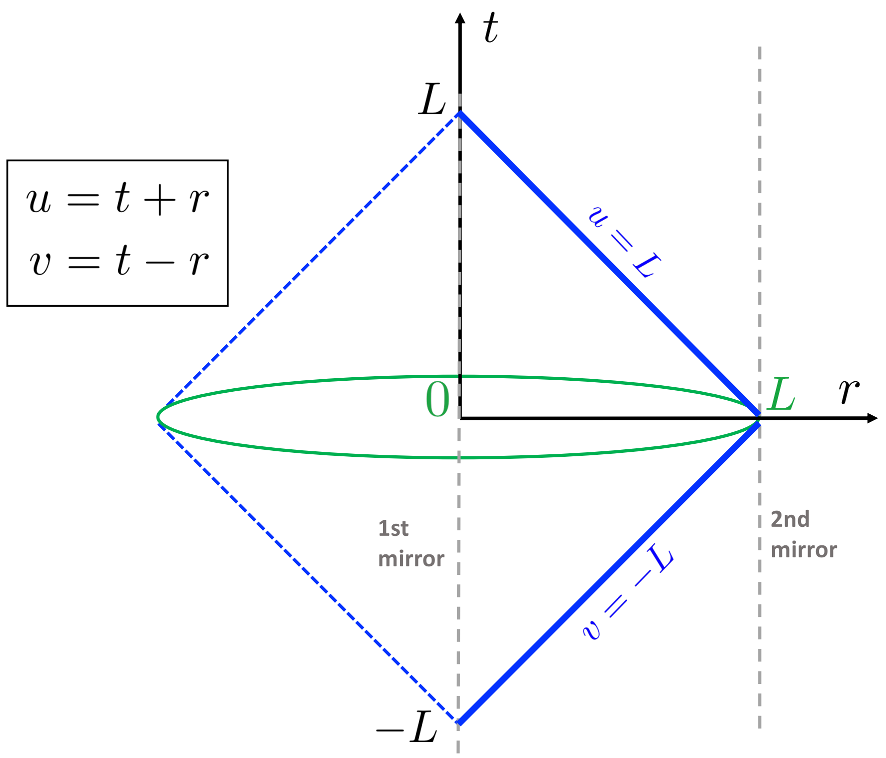
WHAT ARE WE TESTING?

- Fundamental uncertainty in light ray operators…

$$X^v(y) = \tilde{\ell}_p^2 \int_{-L}^{L} du \int d^{d-2}y' f(y,y')\, T_{uu}(u,y')$$

$$X^u(y) = \tilde{\ell}_p^2 \int_{-L}^{L} dv \int d^{d-2}y' f(y,y')\, T_{vv}(v,y').$$



$$\langle X^u(\Omega) X^v(\Omega') \rangle = \tilde{l}_p^{\,2} f(\Omega,\Omega')$$

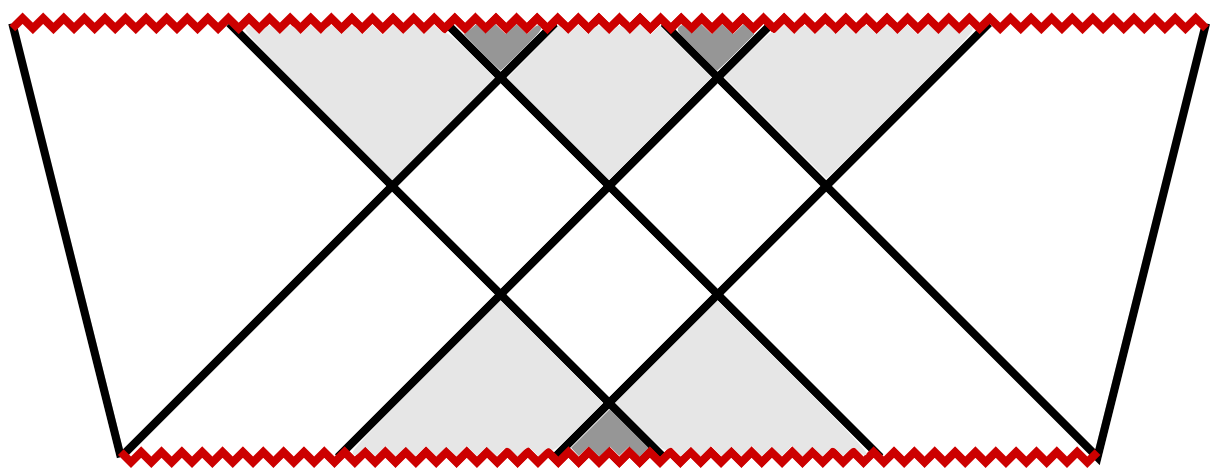
$$X^u(u,\Omega) = L - u + \delta u(u,\Omega)$$

$$\langle K \rangle = \langle (\Delta K)^2 \rangle = \frac{A_\Sigma}{4G}$$

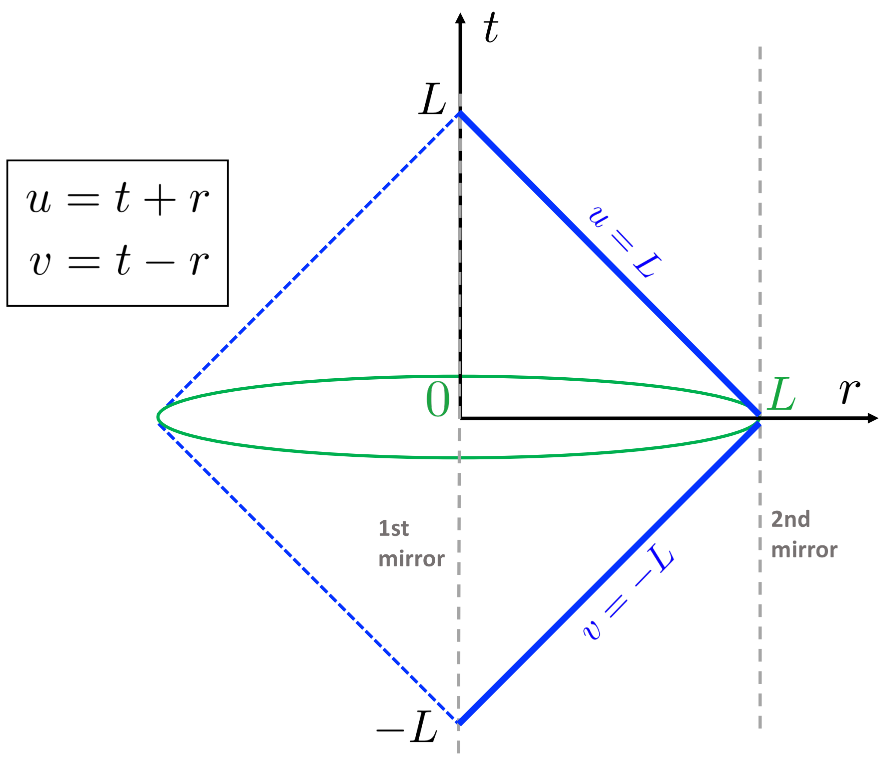
Verlinde, KZ in progress

WHAT ARE WE TESTING?

- **Fundamental uncertainty** in light ray operators…



Multiple shocks



$$\langle X^u(\Omega) X^v(\Omega') \rangle = \tilde{l}_p^{\,2} f(\Omega, \Omega')$$

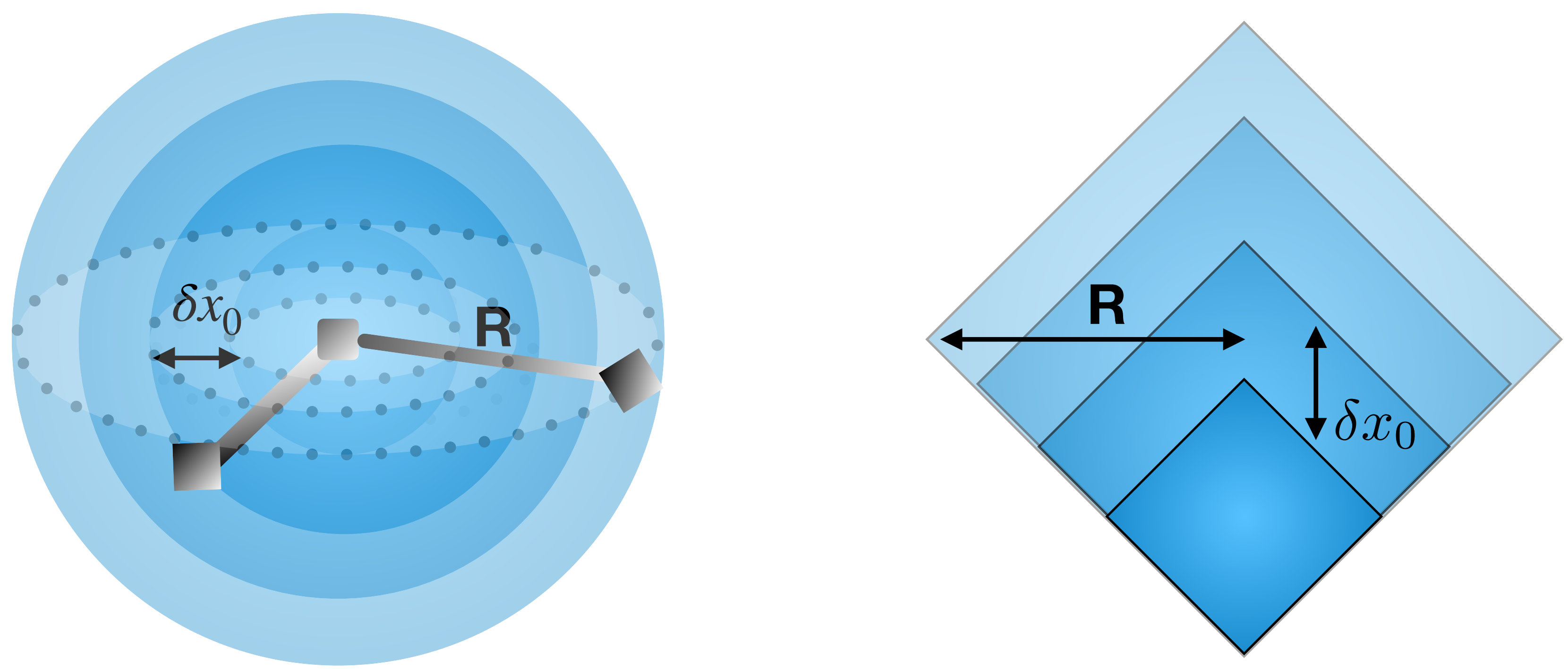
$$X^u(u, \Omega) = L - u + \delta u(u, \Omega)$$

$$\langle K \rangle = \left\langle (\Delta K)^2 \right\rangle = \frac{A_\Sigma}{4G}$$

Verlinde, KZ in progress

WHAT ARE WE TESTING?

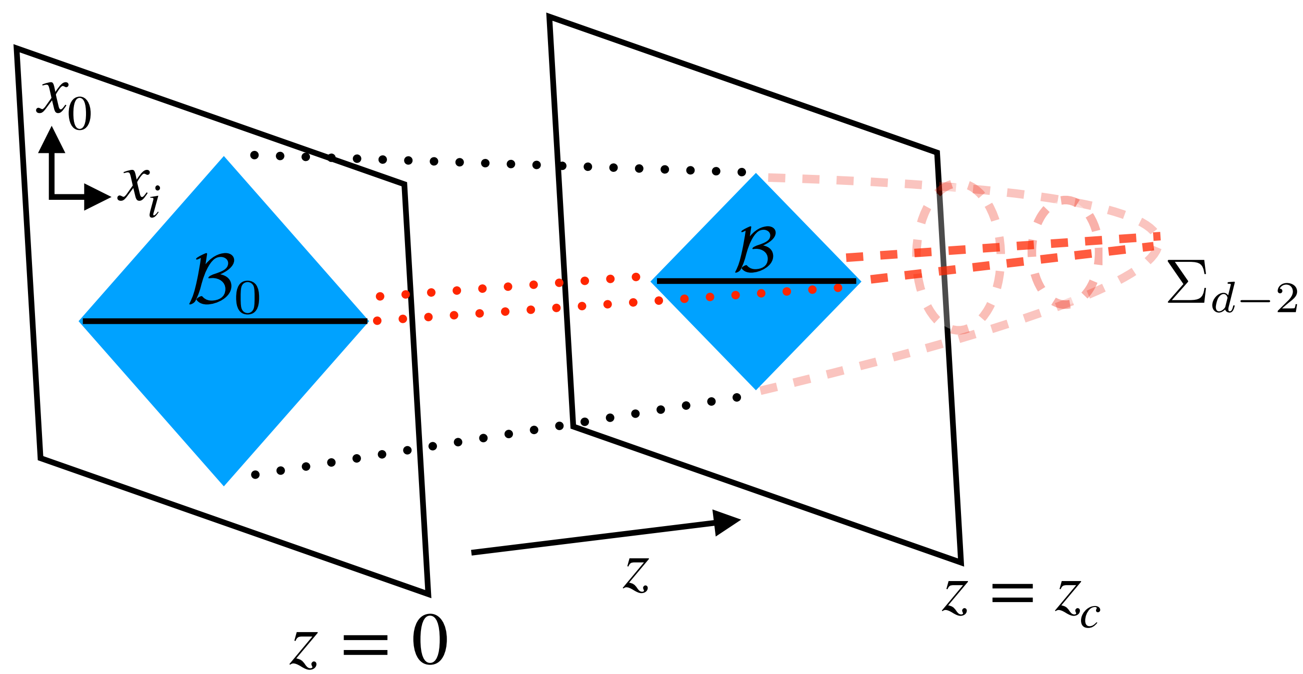
- And their Accumulation into Infrared



$$\delta R^2 \simeq \delta x_0^2\, \mathcal{N} = \frac{R^2}{d-2}\frac{1}{\sqrt{S_0}}$$

EQUIVALENT PHYSICAL DESCRIPTIONS

- In AdS/CFT, a theoretically controlled environment



$$\frac{\Delta T^2}{T^2} = \frac{2}{d-2}\sqrt{\frac{4G}{A(\Sigma)}}$$

Banks, KZ 2108.04806

EQUIVALENT PHYSICAL DESCRIPTIONS

- Hydrodynamics

Linearized Einstein Equation:

$$\Box h^{mn} - \partial_k(\partial^m h^{nk} + \partial^n h^{mk}) + \partial^m \partial^n h^k_k = 0$$

In light cone coordinates leads to a Navier-Stokes equation:

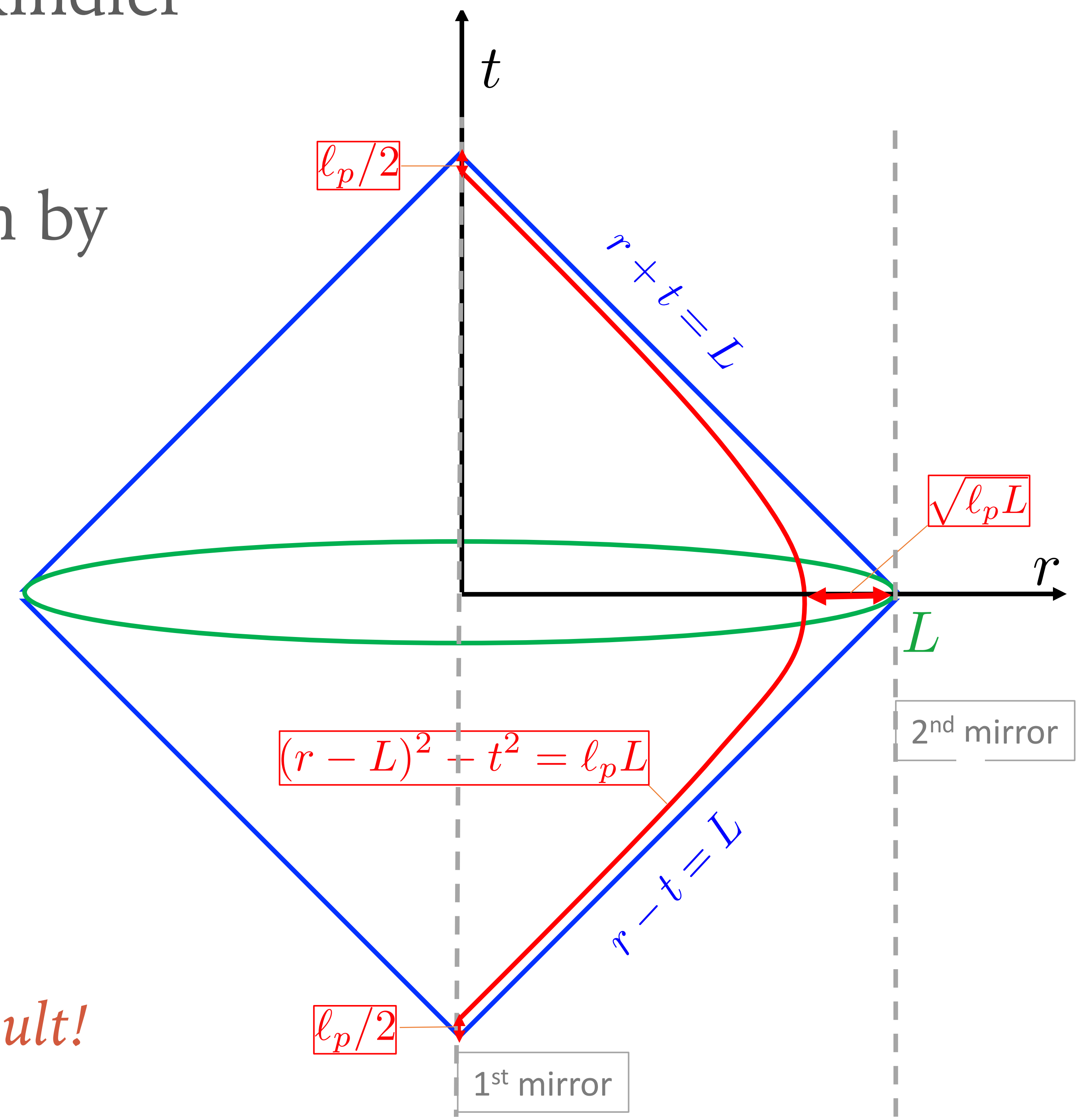
$$\partial_+ h^{mn} = D\nabla^2_a h^{hm}$$

$$D = \partial_-^{-1} \sim l_p \quad \Rightarrow \quad \delta L \sim \sqrt{l_p L}$$

Banks, Keeler, KZ in progress

EQUIVALENT PHYSICAL DESCRIPTIONS

- Description in terms of Rindler Observers
- (fixed) Acceleration given by quantum uncertainty

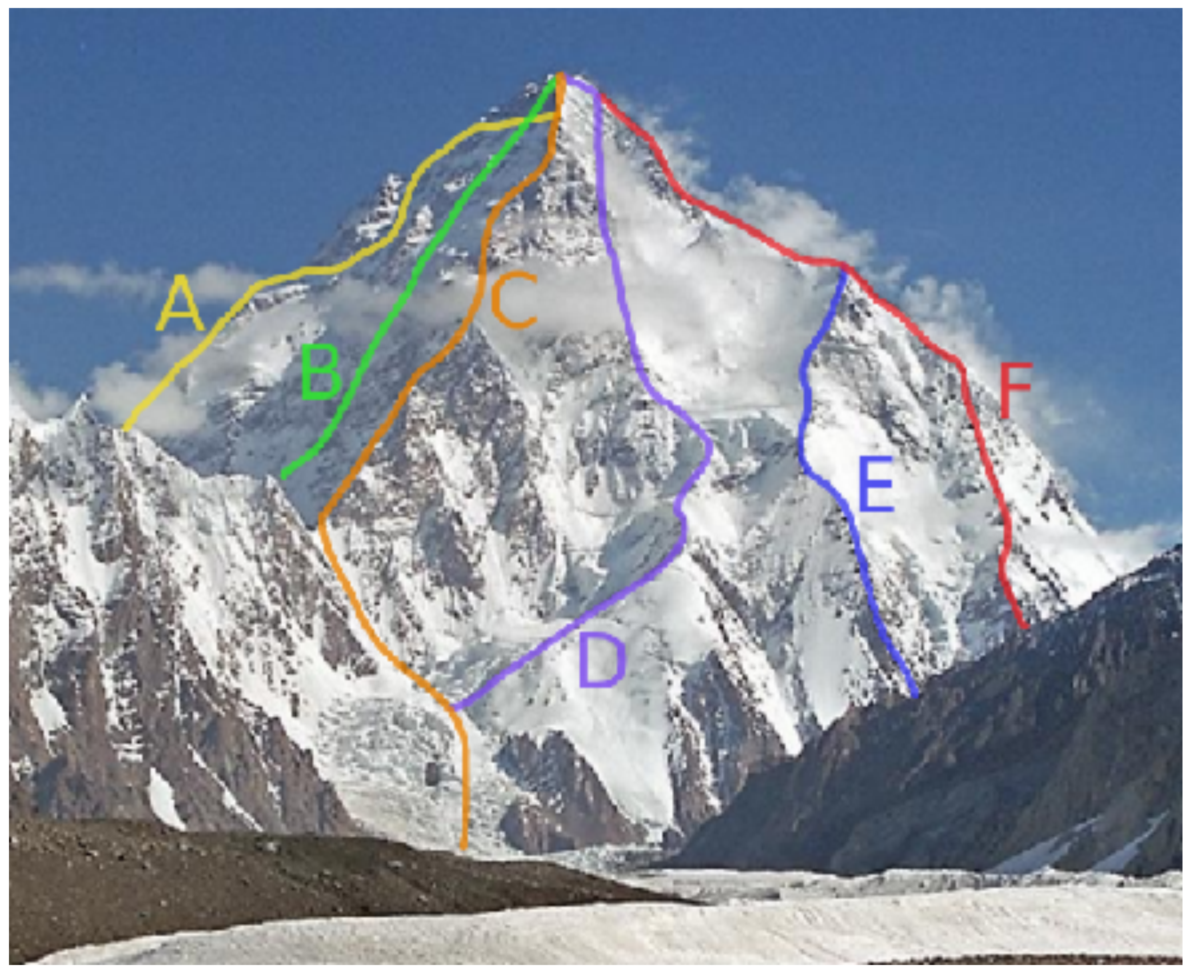


All descriptions give same result!

ONE MOUNTAIN, MANY FACES

F. 2-d Models, e.g. JT gravity *w/ Gukov, Lee*

A. AdS/CFT



E. Hydrodynamics EFT *w/ Banks, Keeler*

B. Light Ray Operators

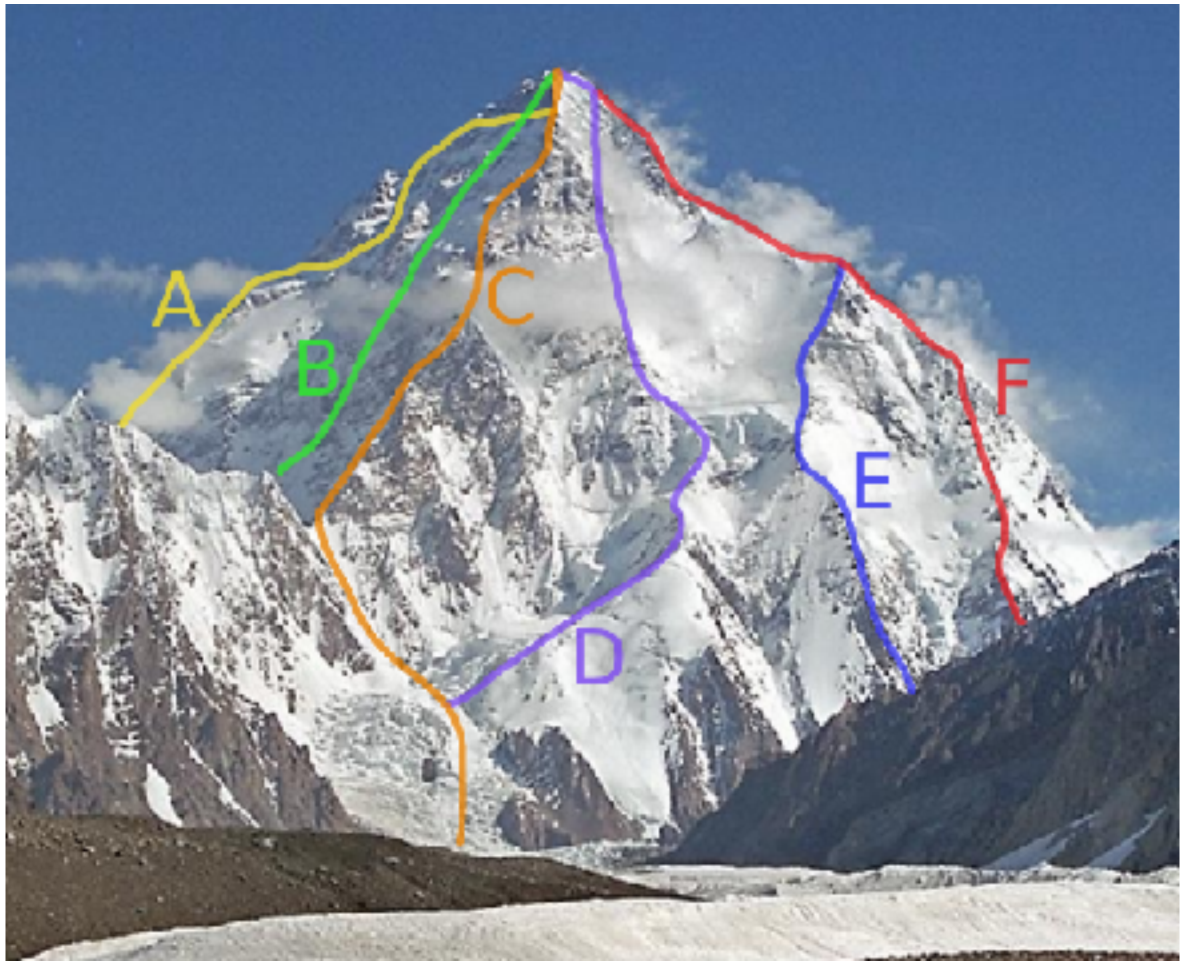
w/ Verlinde

D. TOCs/OTOCs

C. EFT with Feynman-Vernon influence functional *w/ Chen, Li*

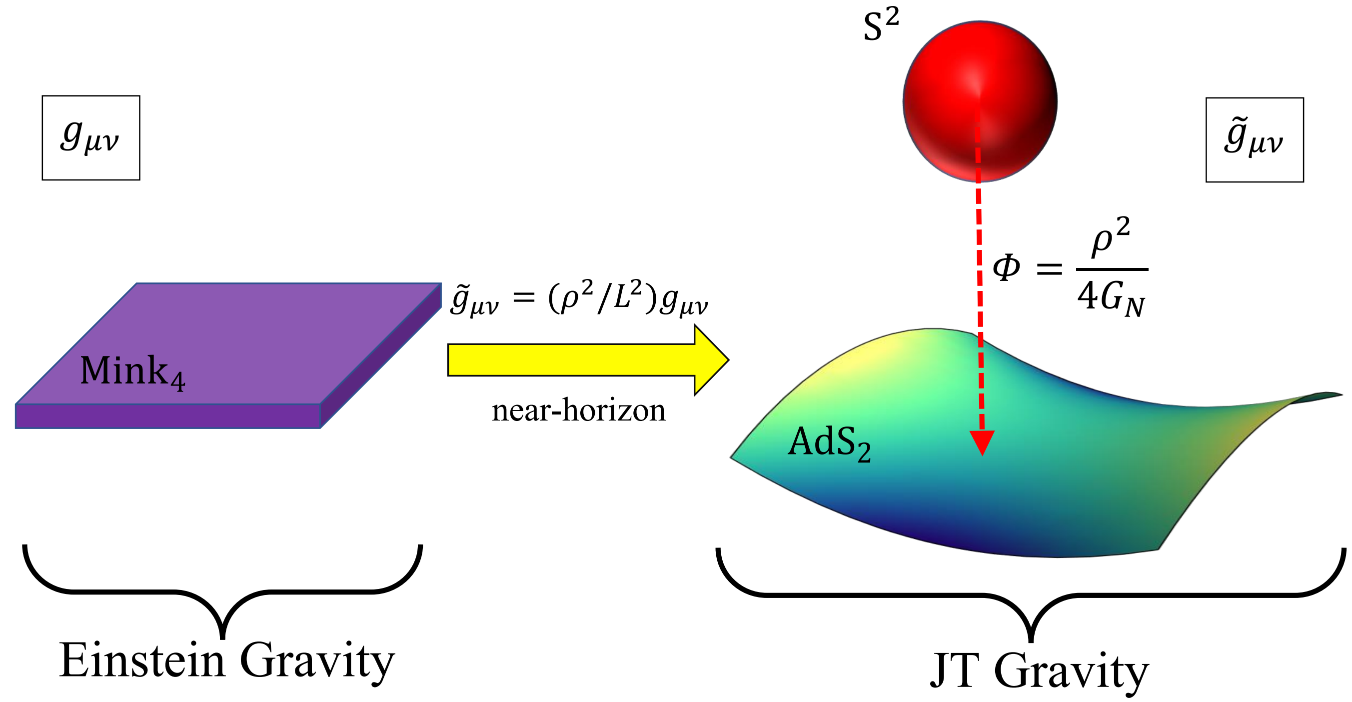
WHAT ROUTE TO THEORETICAL BREAKTHROUGHS DO OBSERVATIONAL SIGNATURES OFFER?

- Utilizing known tools for new questions
    - Leads to novel approaches
    - e.g. flat space holography
    - e.g. bulk reconstruction
    - Creating a new dictionary
- What is the simplest description?
- Experiments sharpen the theoretical mind



WHAT ROUTE TO THEORETICAL BREAKTHROUGHS DO OBSERVATIONAL SIGNATURES OFFER?

- Utilizing known tools for new questions
  - e.g. in near horizon limit, 4-d Einstein-Hilbert action dimensionally reduces to Jackiw-Teitelboim gravity in 2-d



$$I = \int_{\tilde{M}_2} d^2x \sqrt{-\tilde{g}_2}\Phi\left(\tilde{R}_2 + \frac{2}{L^2}\right) + 2\int_{\partial\tilde{M}_2} dx^0 \sqrt{-\tilde{\gamma}_1}\Phi\tilde{K}_1$$

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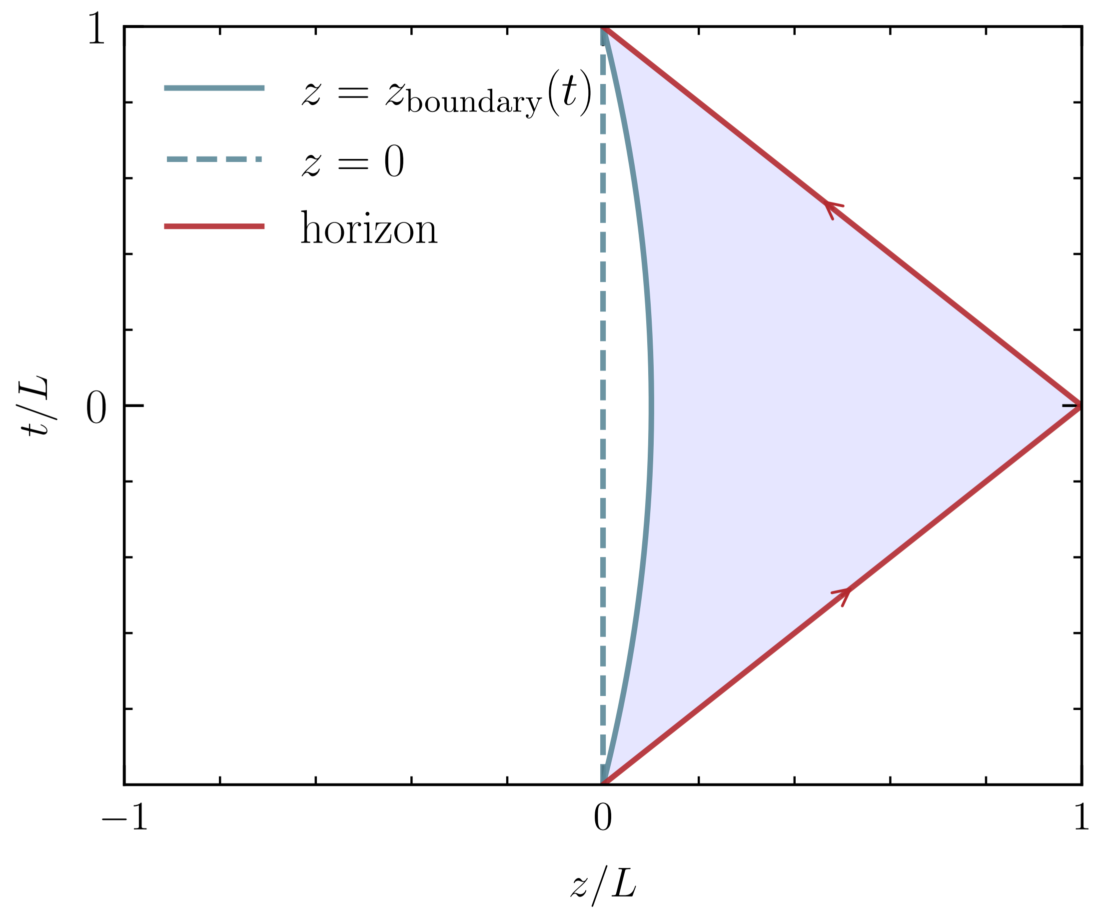
WHAT ROUTE TO THEORETICAL BREAKTHROUGHS DO OBSERVATIONAL SIGNATURES OFFER?

- Utilizing known tools for new questions
  - JT gravity reduces to 1-d QM problem that can be solved exactly



$$\frac{\Delta T^2_{\text{r.t.}}}{T^2_{\text{r.t.}}} = \frac{1}{\sqrt{2S}}$$
$$= \frac{l_p}{4\pi L}$$

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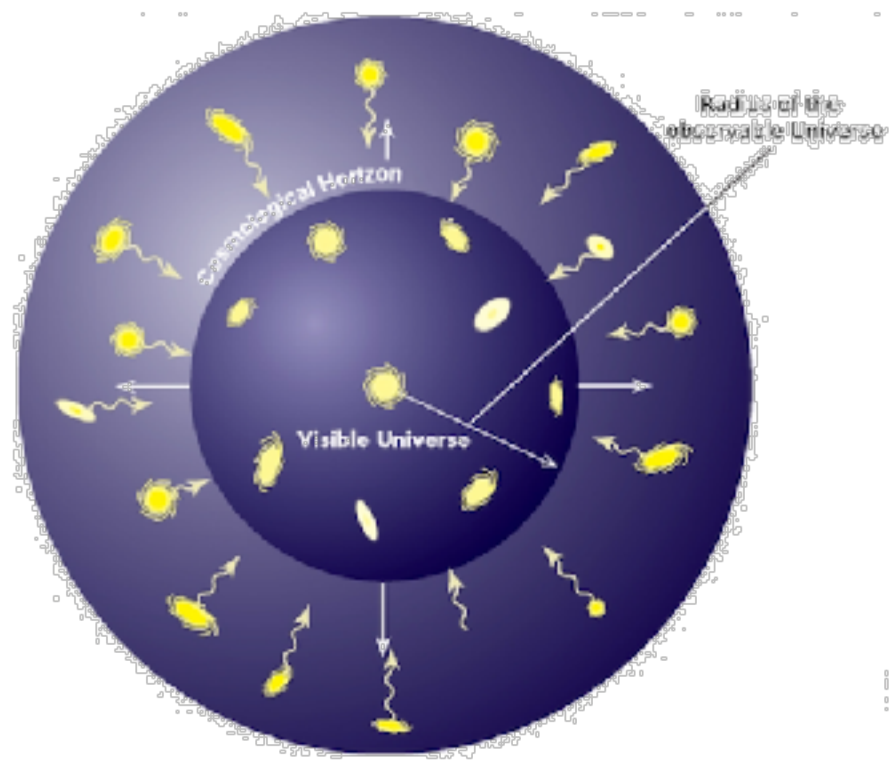
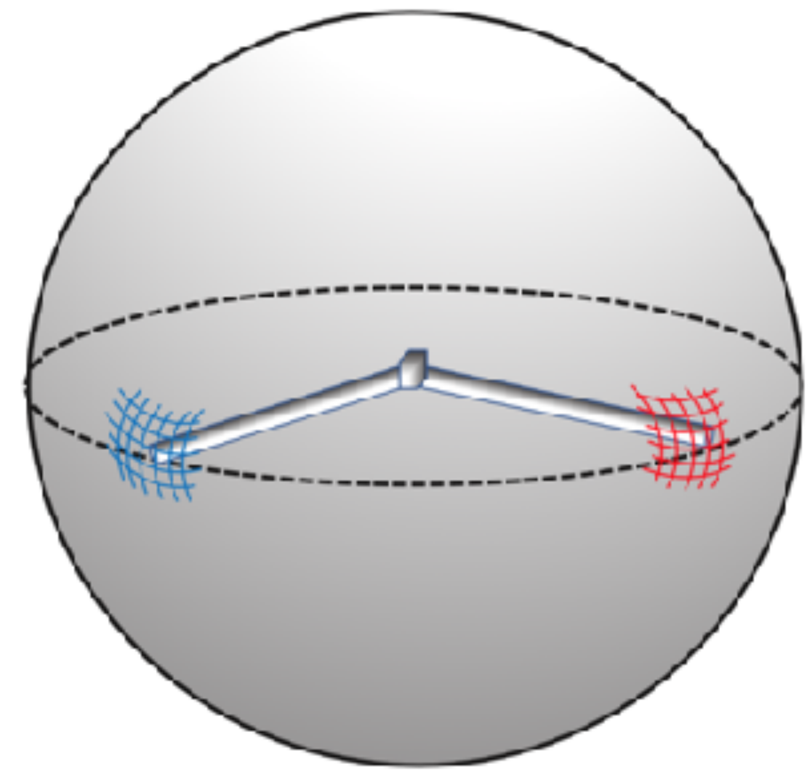
SEARCHING FOR THE NEW HYDROGEN ATOM?

Black Hole Horizon



Cosmological Horizon



Flat Space Horizon