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

Ann-Fest 2022

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Based on work with:

Verlinde 1902.08207, 1911.02018, in progress

KZ 2012.05870

Banks 2108.04806

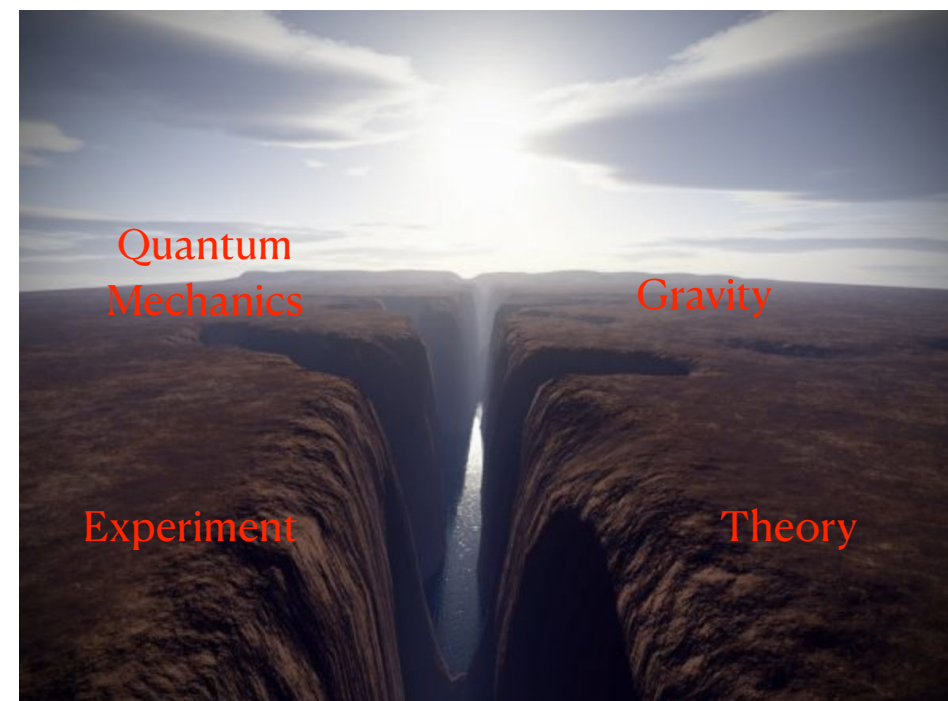
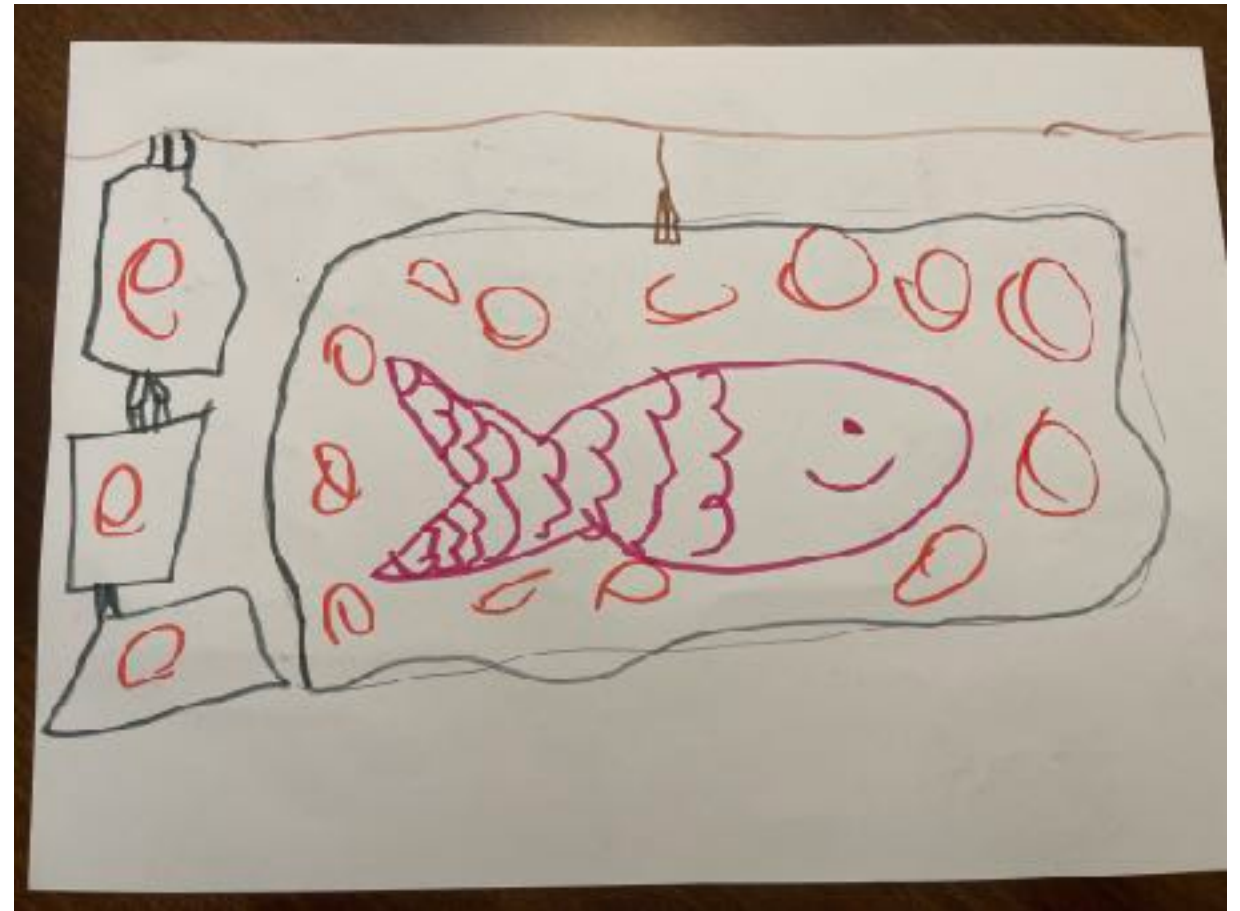
Gukov, Lee, 2205.02233

Please see Snowmass whitepaper for summary of this talk, 2205.01799

Kathryn M. Zurek

MODEL BUILDING IS LIKE....

- A fish, painted purple, hanging on a string, on a shelf, on the wall
- Model building requires some adventure-seeking and norm-bending path finding
- It may turn out to be the most natural thing in the world — “I’m not sure why they call it anomalous because it’s exactly what the theory predicts”
- We need model builders in QG



SEARCHING FOR UV PHYSICS OF QG IN THE IR

➤ A model-builder's adventurous spirit

Effective Field Theory, Black Holes, and the Cosmological Constant

Andrew G. Cohen^a, David B. Kaplan^b and Ann E. Nelson^c

Bekenstein has proposed the bound $S \leq \pi M_P^2 L^2$ on the total entropy S in a volume L^3 . This non-extensive scaling suggests that quantum field theory breaks down in large volume. To reconcile this breakdown with the success of local quantum field theory in describing observed particle phenomenology, we propose a relationship between UV and IR cutoffs such that an effective field theory should be a good description of Nature. We discuss implications for the cosmological constant problem. We find a limitation on the accuracy which can be achieved by conventional effective field theory: for example, the minimal correction to $(g - 2)$ for the electron from the constrained IR and UV cutoffs is larger than the contribution from the top quark.

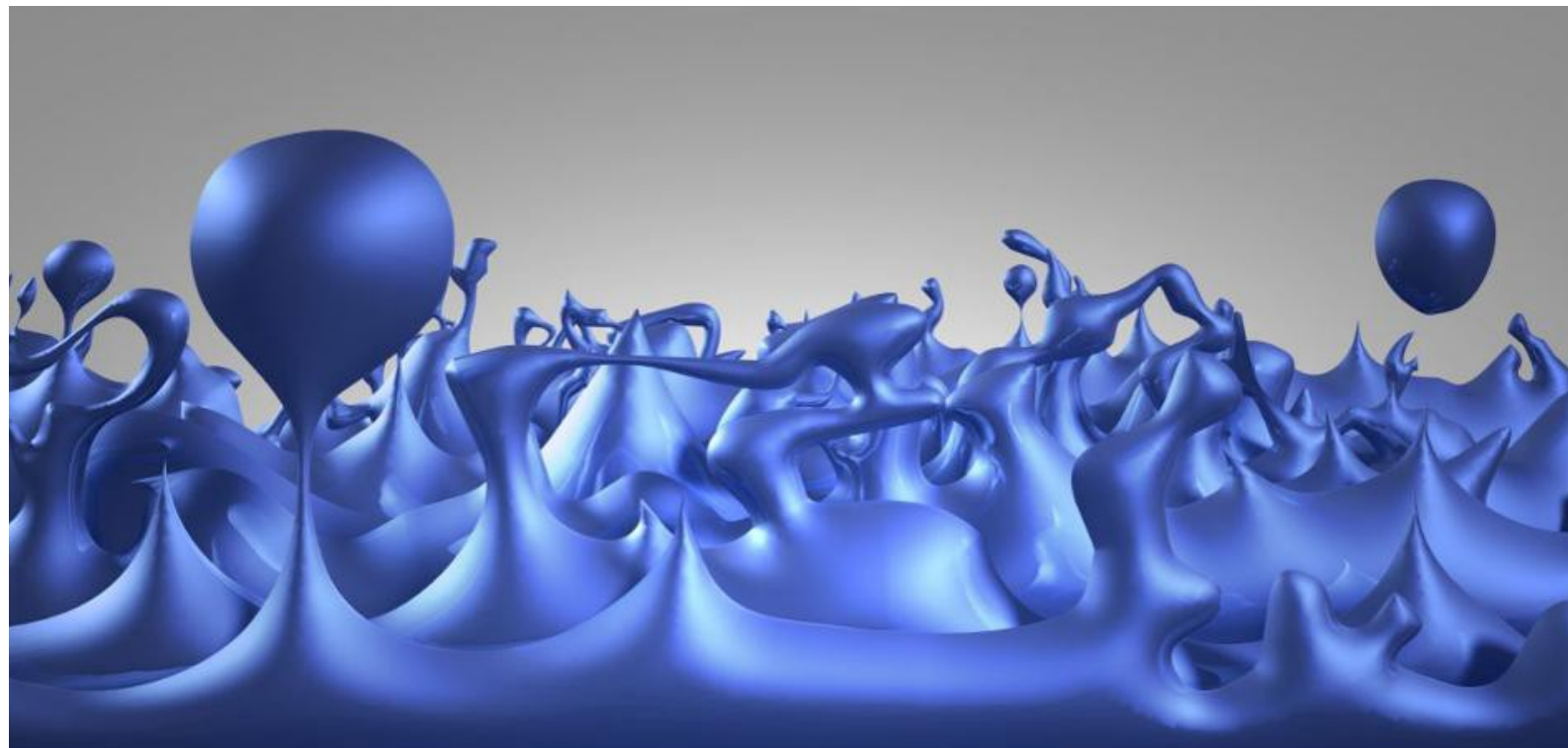
SEARCHING FOR UV PHYSICS OF QG IN THE IR

- A model-builder's adventurous spirit
- Since this paper appeared we have learned a lot about the structure of QG in the IR, and the path we will follow will use more traditional QG tools (though not in the way envisioned by their authors)
- Nevertheless take the model builder's spirit — try to see what QG can do in the IR consistent with its rules, setting preconceived notions aside

QUANTUM GRAVITY

—> FLUCTUATIONS IN SPACETIME

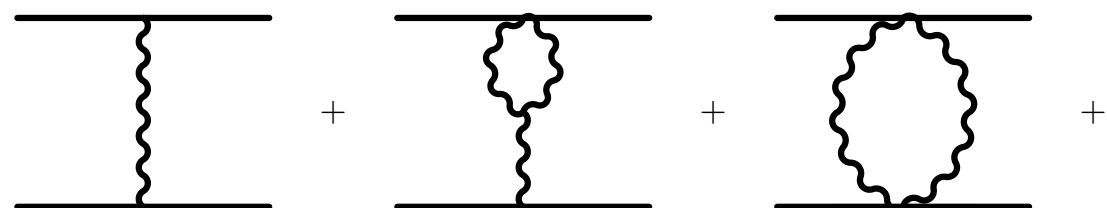
OLD VIEW: VISIBLE ONLY AT ULTRASHORT DISTANCES



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

PERTURBATIVELY, THERE SHOULD BE NO OBSERVATIONAL EFFECTS

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



The image shows three Feynman diagrams representing the perturbative expansion of the gravitational potential. Each diagram consists of two horizontal lines representing external particles, connected by a vertical line representing a graviton. The first diagram shows a simple vertical wavy line. The second diagram shows a vertical wavy line with a small loop (self-energy) on it. The third diagram shows a vertical wavy line with a larger loop (polarization) on it. These diagrams are separated by plus signs and followed by an ellipsis, indicating an infinite series.

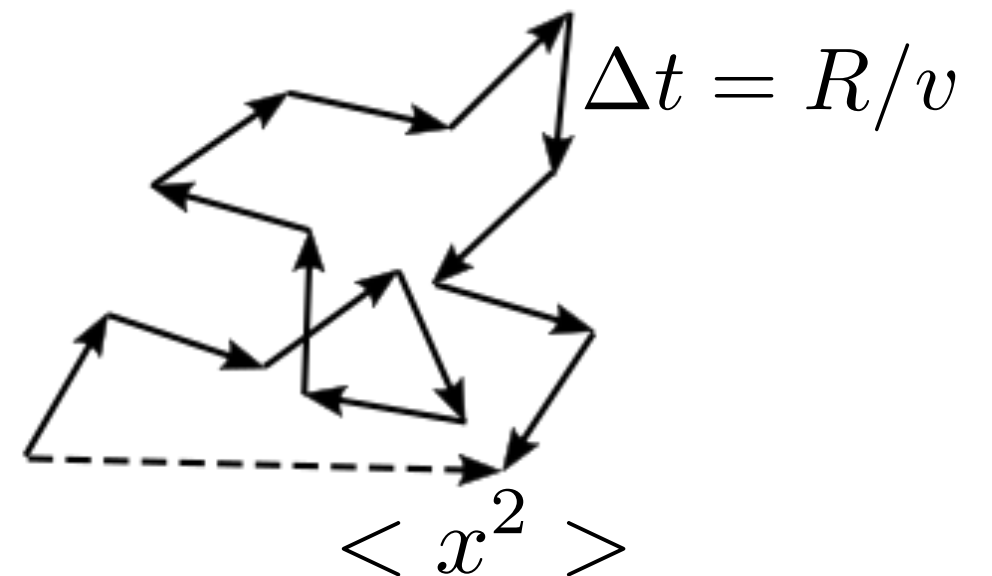
$$V(r) = -\frac{Gm_1m_2}{r} \left(1 + a \frac{G(m_1 + m_2)}{rc^2} + b \frac{G\hbar}{r^2c^3} \right)$$

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



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

$$D \sim \Delta t$$

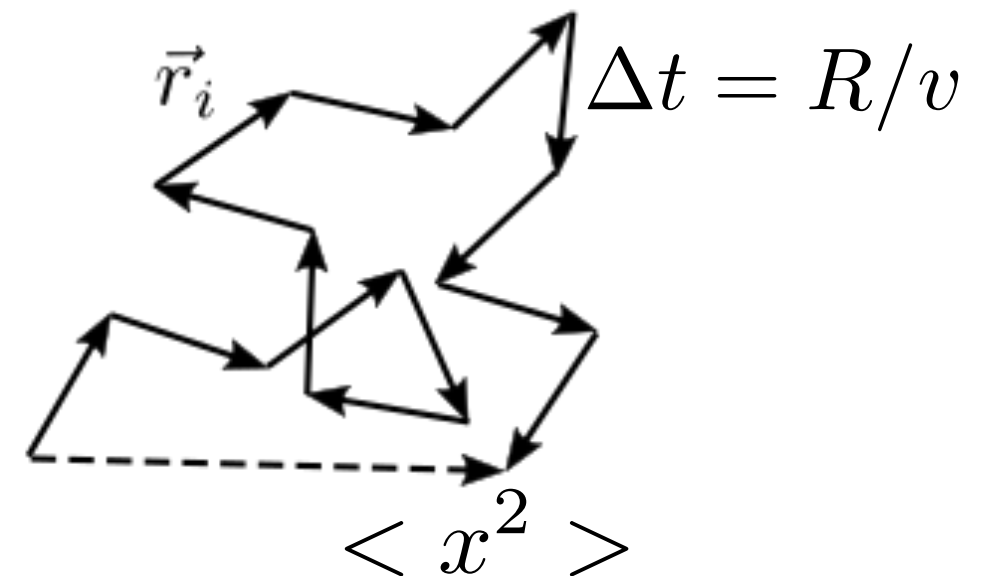
UV Scale

Observing time

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

$$N = \frac{T}{\Delta t}$$

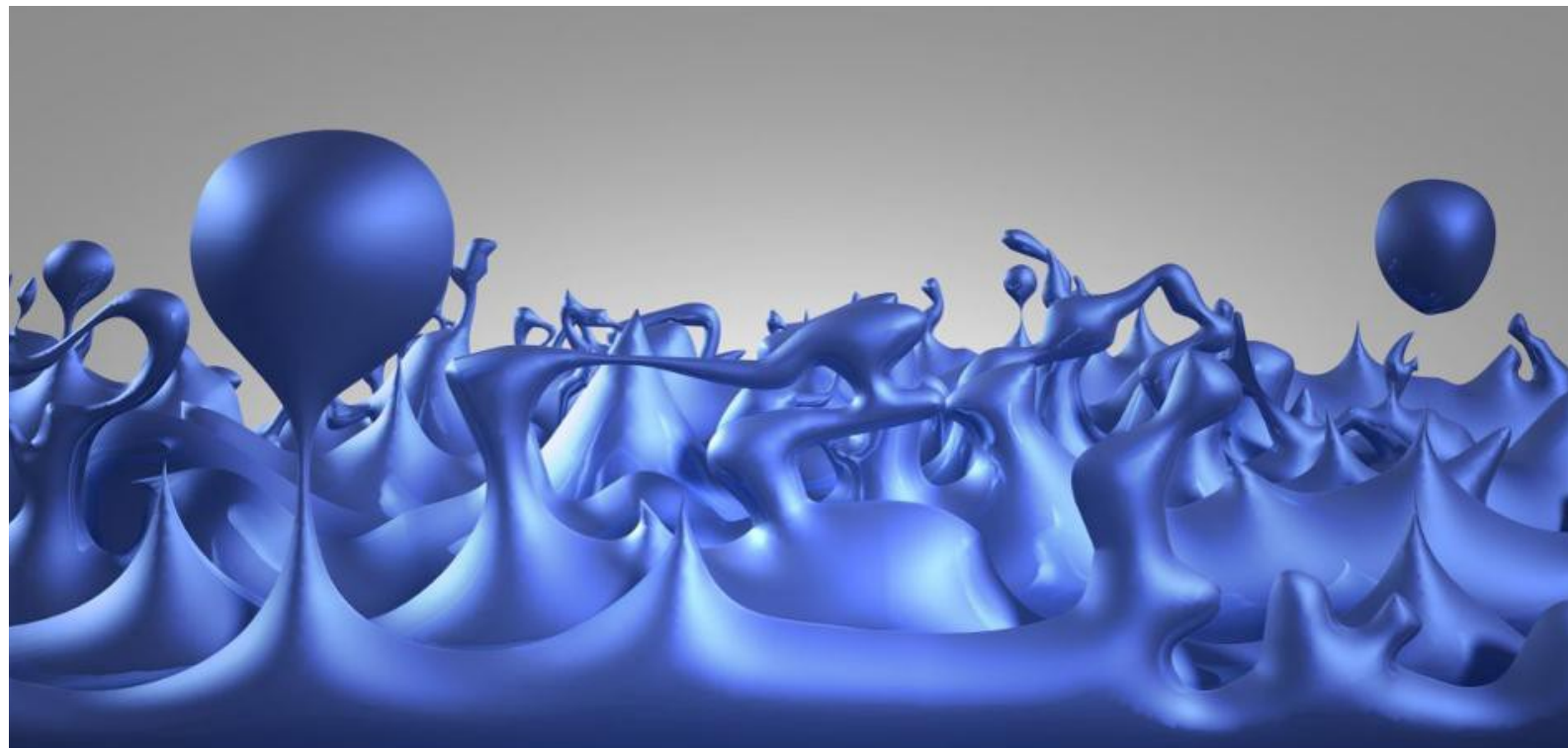
$$\Delta x \sim \sqrt{N} \Delta t$$

Diffusion is simply “Random walk” or “Root N ” statistics

QUANTUM GRAVITY

—> FLUCTUATIONS IN SPACETIME

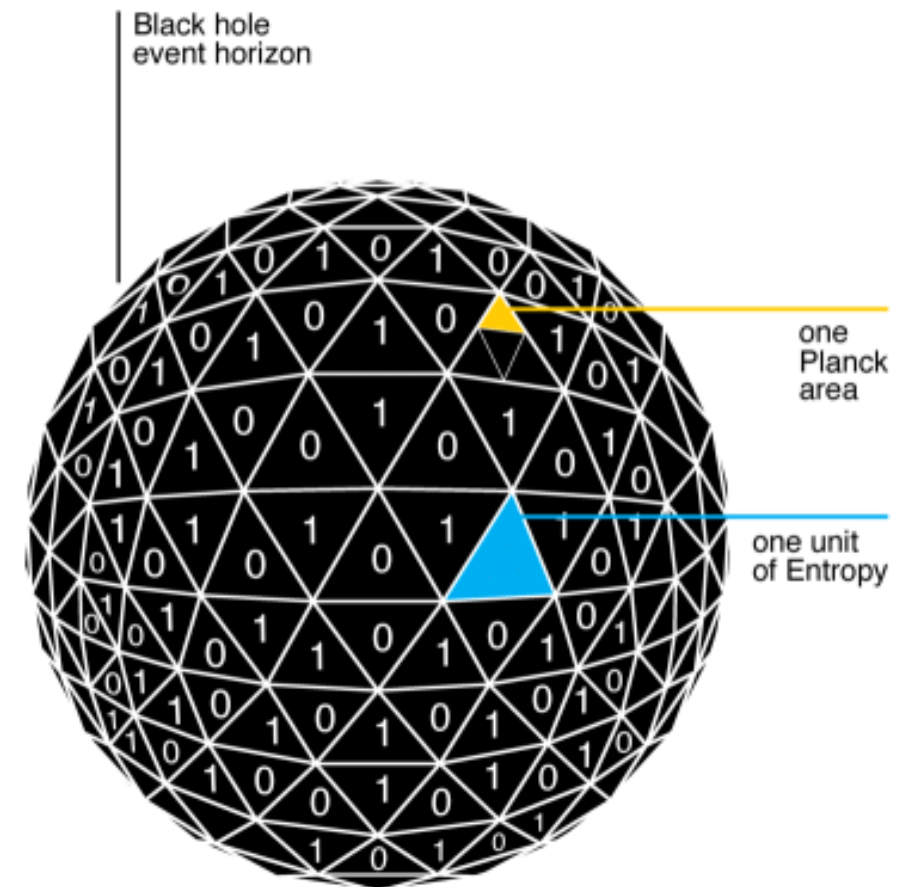
NEW VIEW: INFRARED EFFECTS ARE IMPORTANT



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

PHYSICS AT THE HORIZON

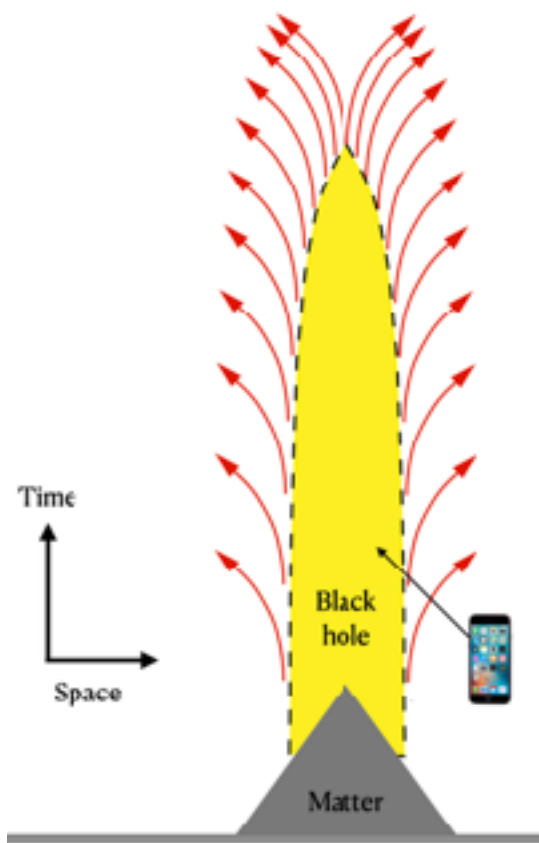
- Physics at horizons enters front and center into holography and QG
- Some naive EFT/ perturbative reasoning breaks down at the horizon
- For example, EFT vastly overcounts degrees-of-freedom of a spacetime volume bounded by surface of area A
- Entanglement between these degrees of freedom — inside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

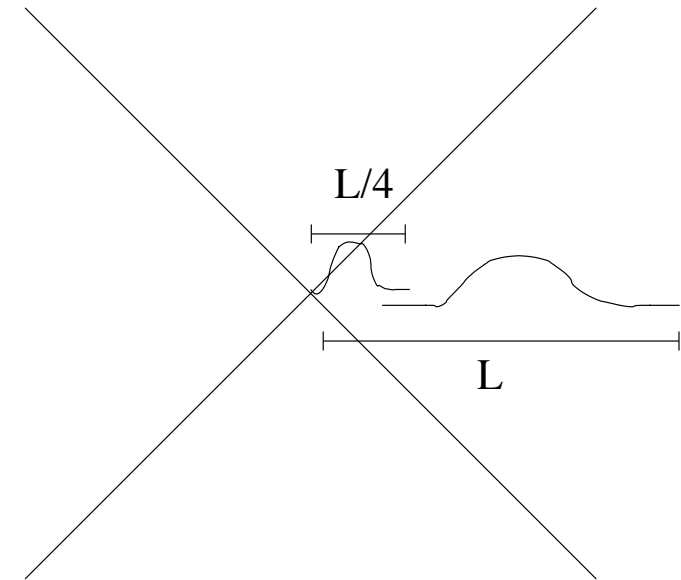
Problem seems to occur at the horizon, where semiclassical gravity should work fine

THE QUANTUM WIDTH OF A (BH) HORIZON

- Degrees-of-freedom (“pixels”) can fluctuate

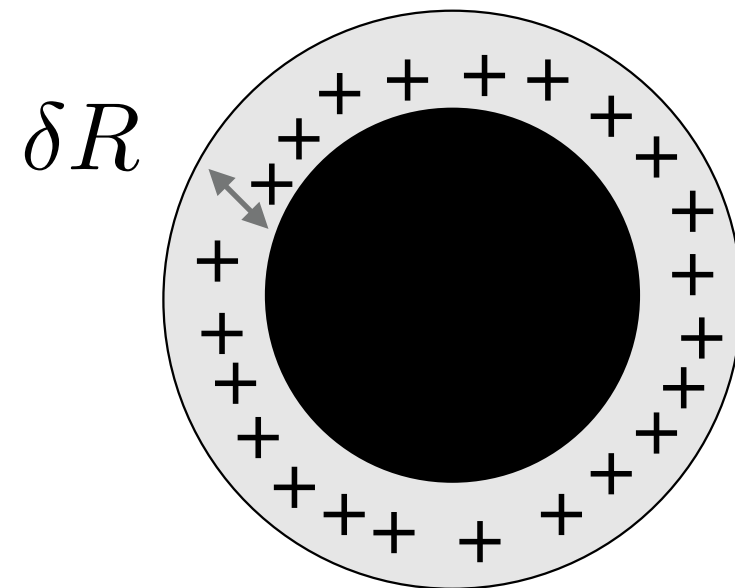
$$\delta R \sim \sqrt{l_p R}$$

$d=4$



In any number of dimensions:

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



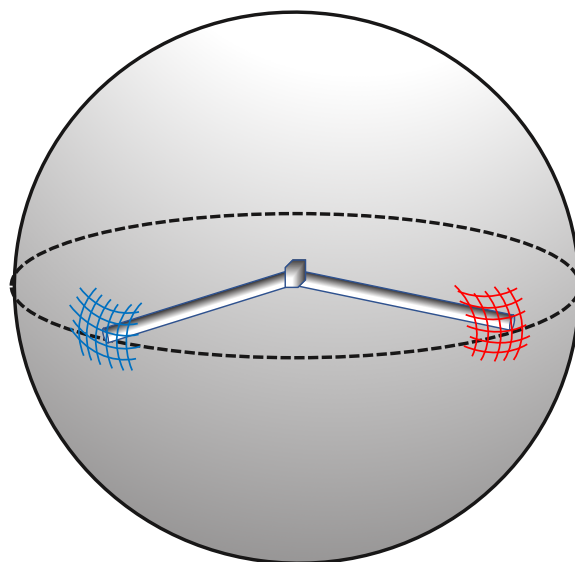
Marolf 2003

HORIZONS AND EXPERIMENTS

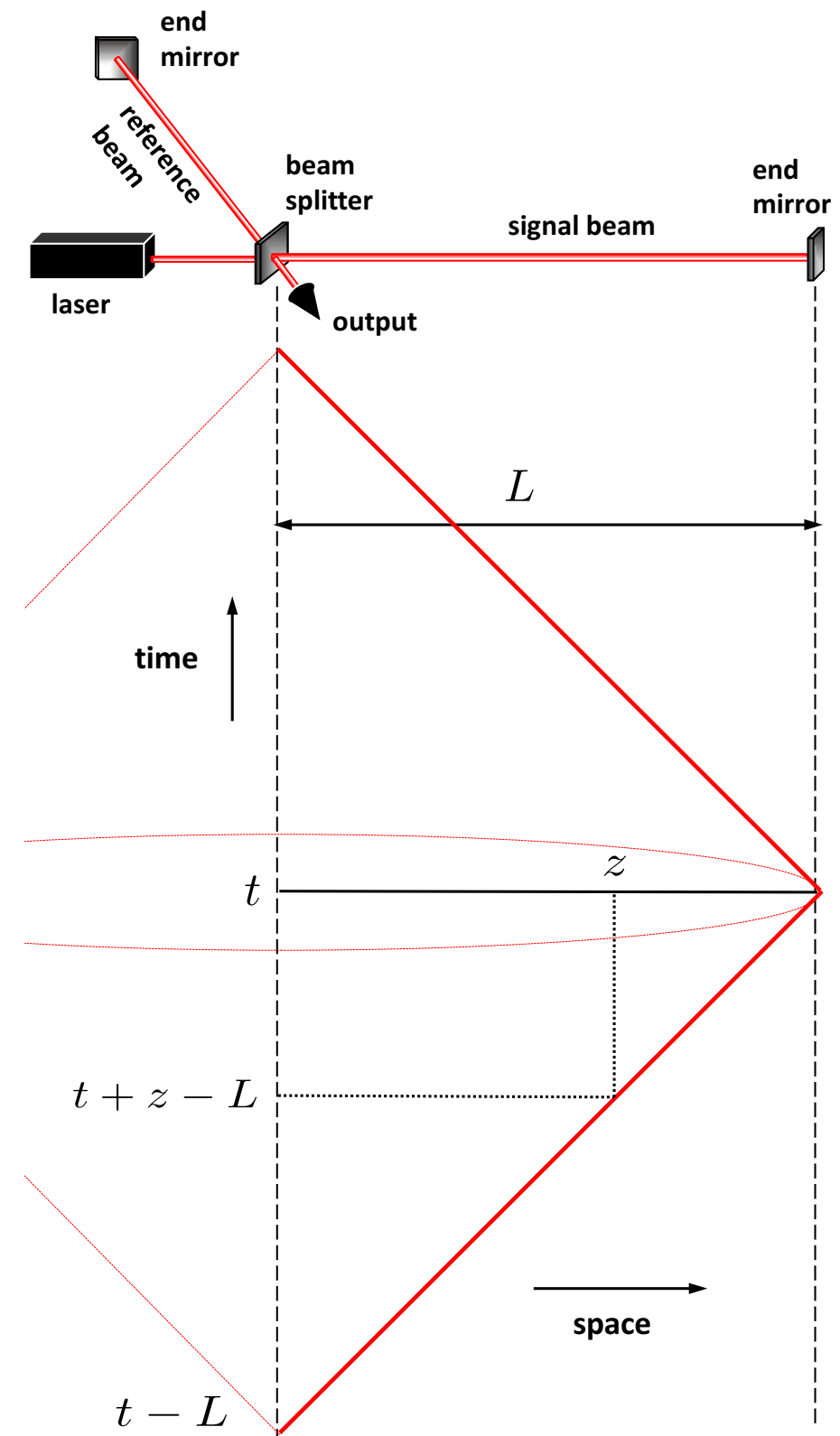
E. Verlinde, KZ 1902.08207

E. Verlinde, KZ 1911.02018

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



- *Traces out a causal diamond*

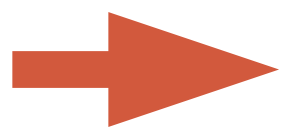


WHAT LENGTH FLUCTUATION CAN BE MEASURED?

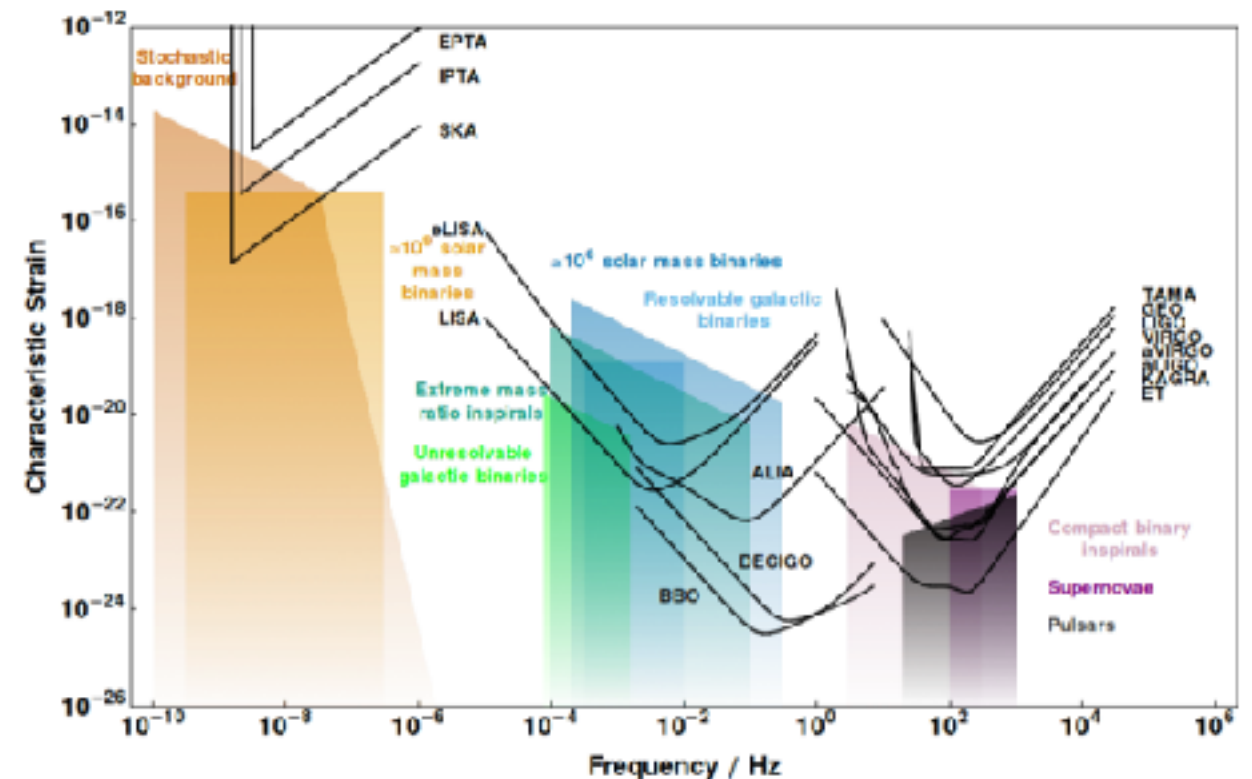
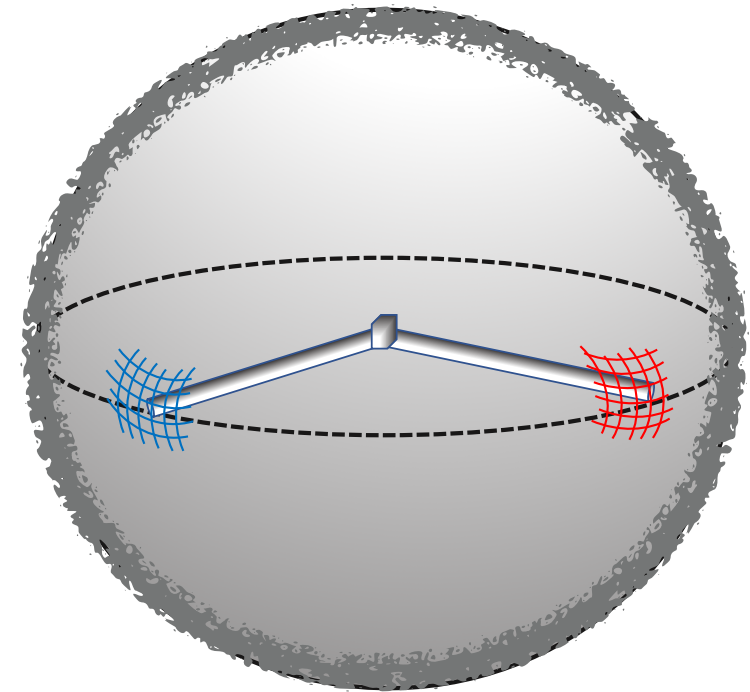
$$\delta L(t) = \frac{1}{2} \int_0^L dz h(t+z-L)$$

Modern Interferometer Set-Up:

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



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



BLACK HOLE – (EMPTY!) CAUSAL DIAMOND DICTIONARY

Black Hole

- Horizon
- Black Hole Temperature
- Black Hole Mass
- Thermodynamic free energy
- Entropy

Causal Diamond

- Horizon Defined by Null Rays
- Size of Causal Diamond

$$T \sim 1/L$$

- Modular Fluctuation

$$M = \frac{1}{2\pi L} \left(K - \langle K \rangle \right)$$

- Partition Function

$$F = -\frac{1}{\beta} \log \text{tr} \left(e^{-\beta K} \right)$$

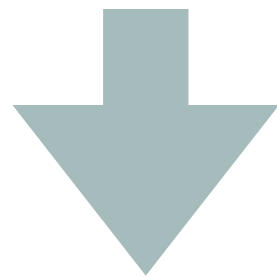
- Entanglement Entropy

$$S = \langle K \rangle = \frac{A}{4G}$$

BLACK HOLES VS. FLAT EMPTY SPACE

- 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”

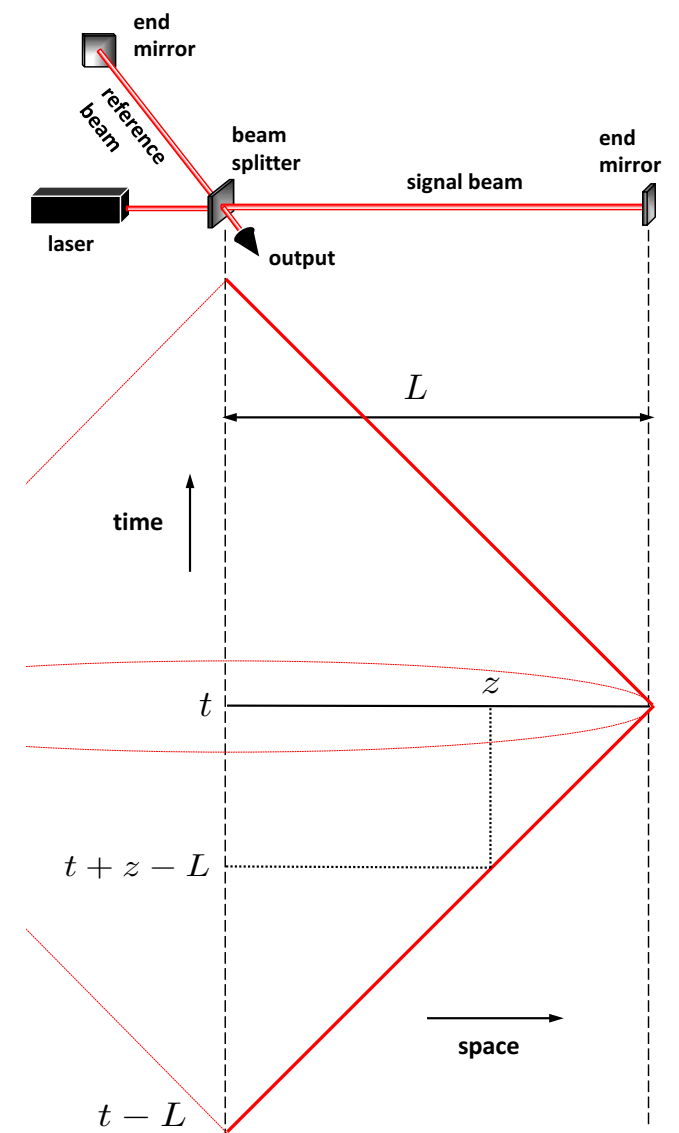
$$ds^2 = dudv + dy^2$$



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

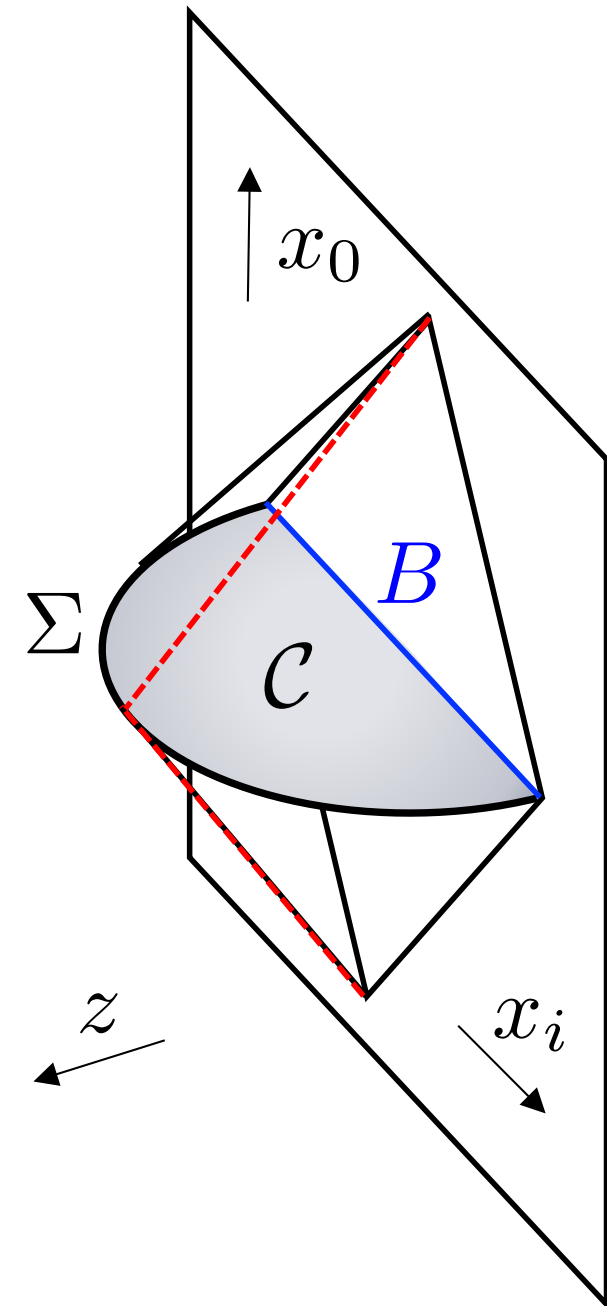
$$f(R) = 1 - \frac{R}{L} + 2\Phi$$

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



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)



OUR ARGUMENT (2 STEPS)

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

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1. Calculate fluctuations in the energy of the vacuum

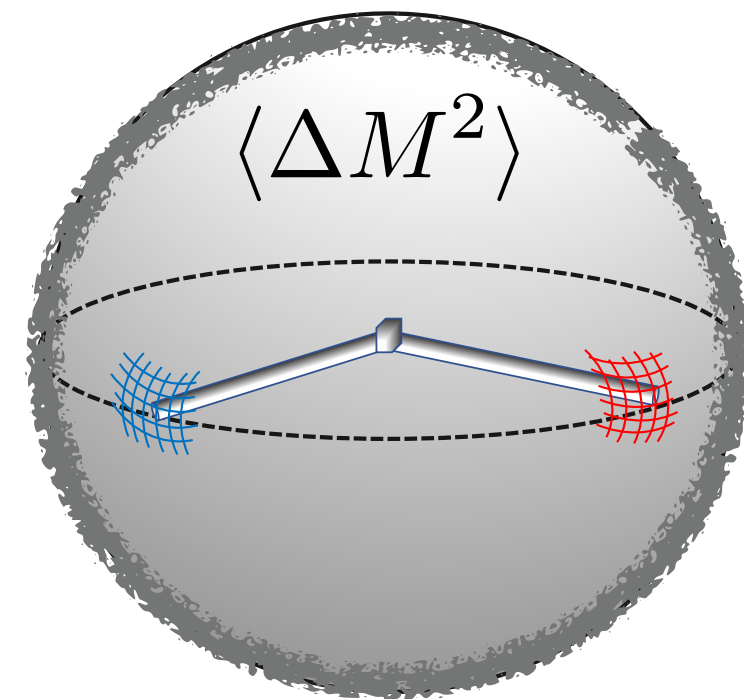
A. In AdS/CFT this can be calculated with no assumptions.

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

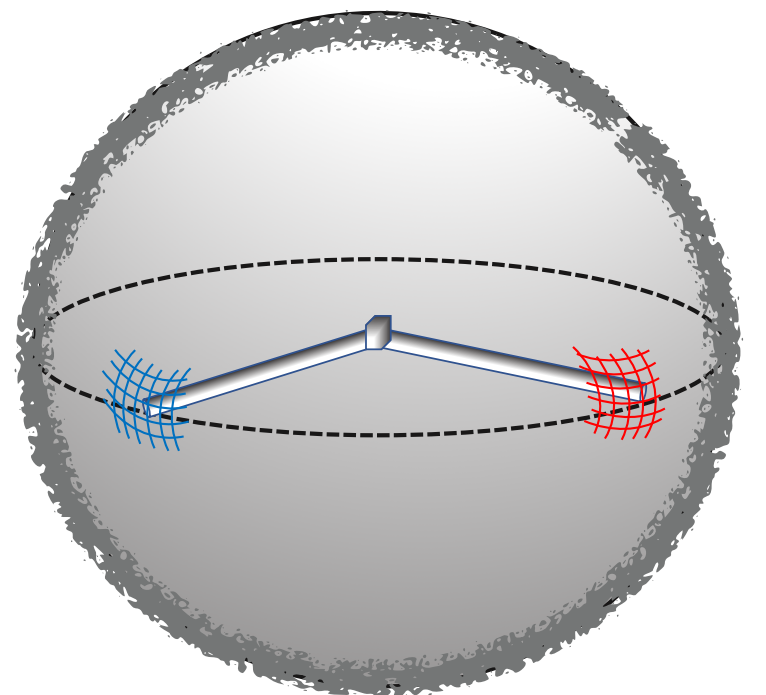
$$S = \frac{A}{4G_N} = \frac{8\pi^2 R^2}{l_p^2}$$

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

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

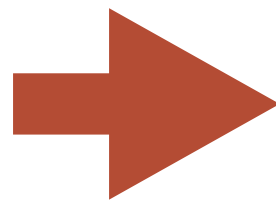
- Statistical argument:

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



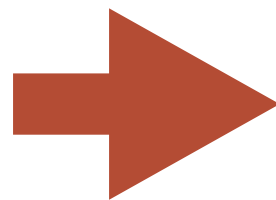
2) VACUUM FLUCTUATION SOURCES METRIC FLUCTUATION

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

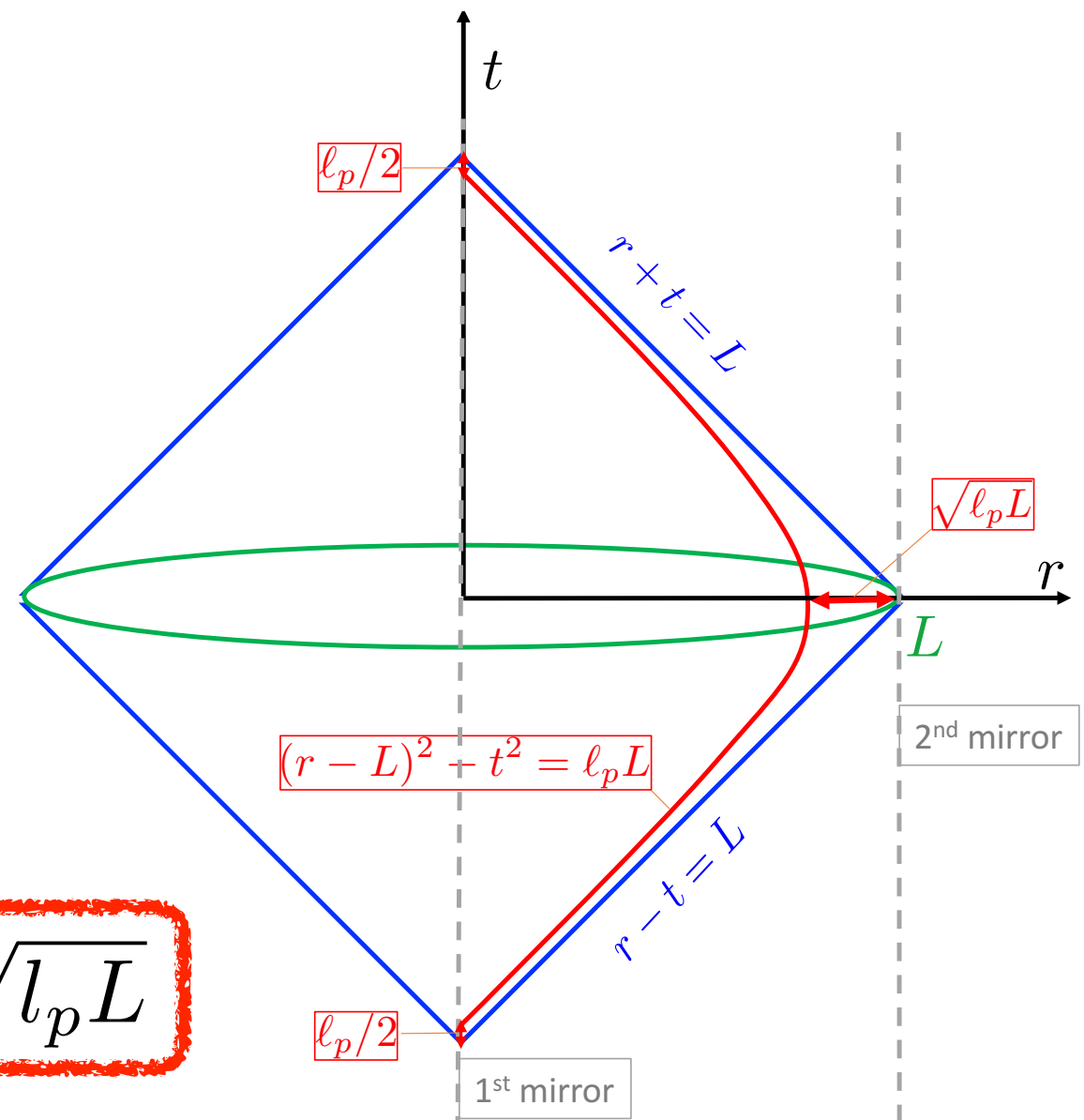


$$\Phi \sim \frac{l_p}{L}$$

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



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



ONE MOUNTAIN, MANY FACES

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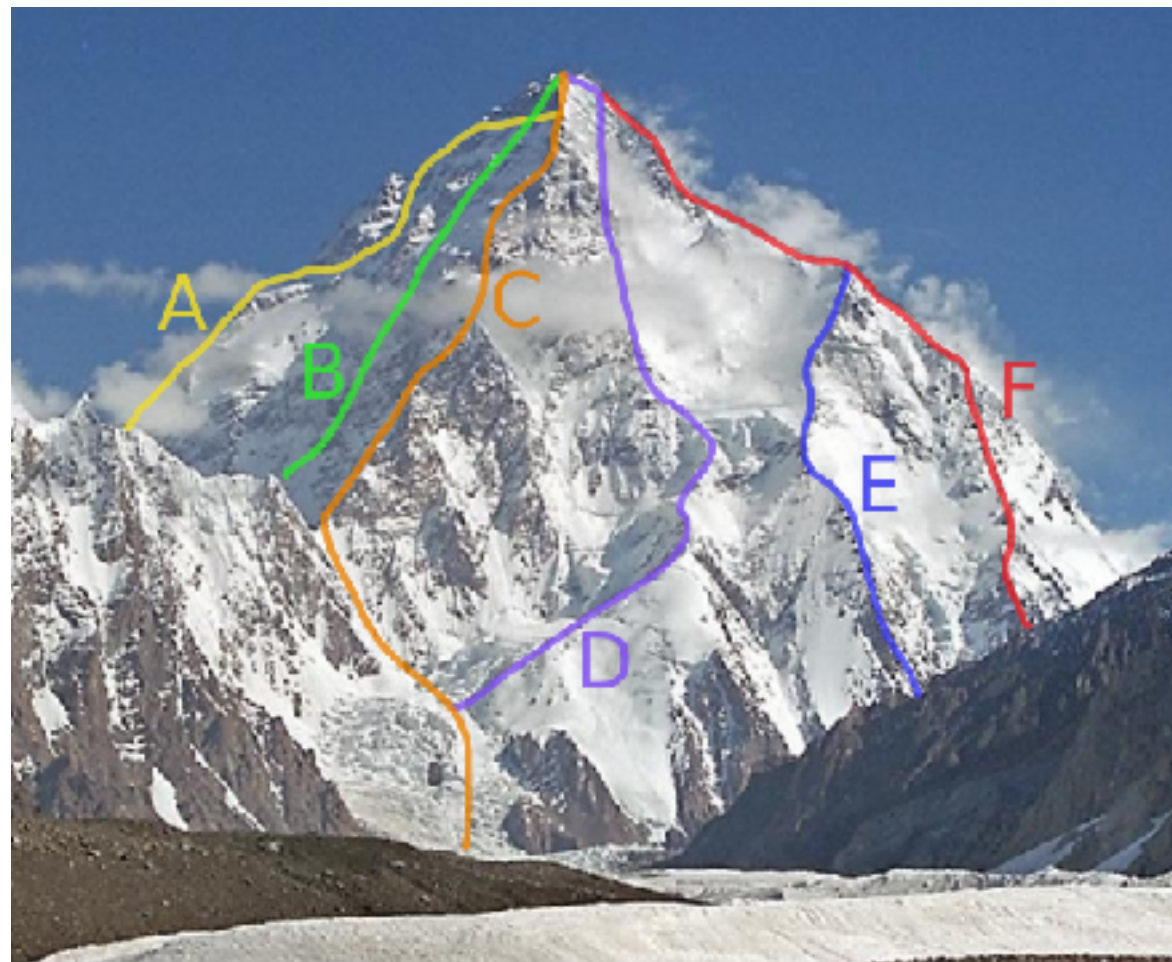
F. 2-d Models, e.g. JT
gravity *w/ Gukov, Lee*

A. AdS/CFT

E. Hydrodynamics EFT
w/ Banks, Keeler

D. TOCs/OTOCs

B. Light Ray
Operators
w/ Verlinde



C. Gravitational effective action /
saddle point expansion *w/ Chen, Li*

EXPERIMENT — GQUEST

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

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

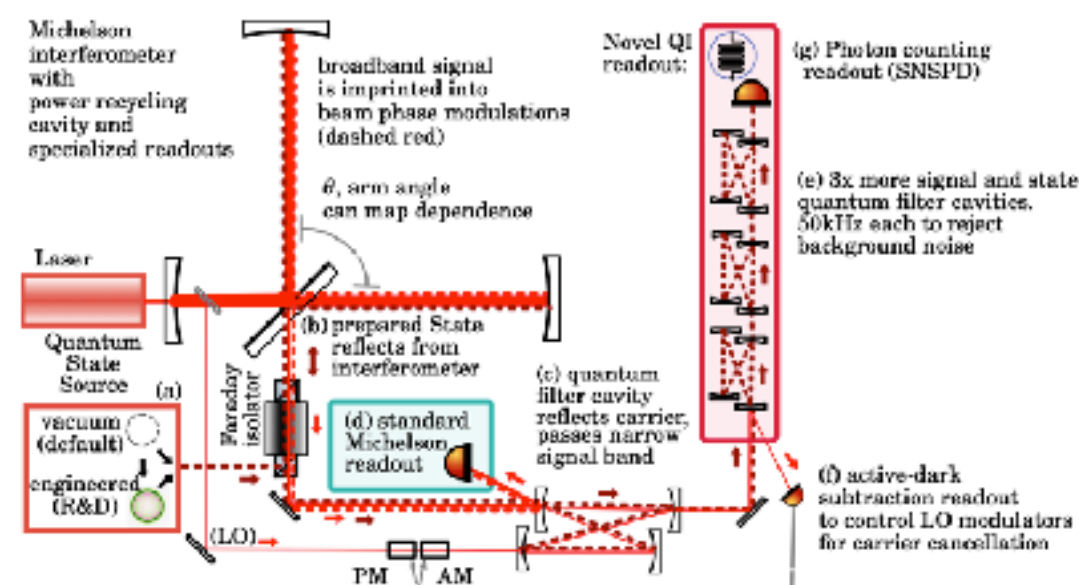


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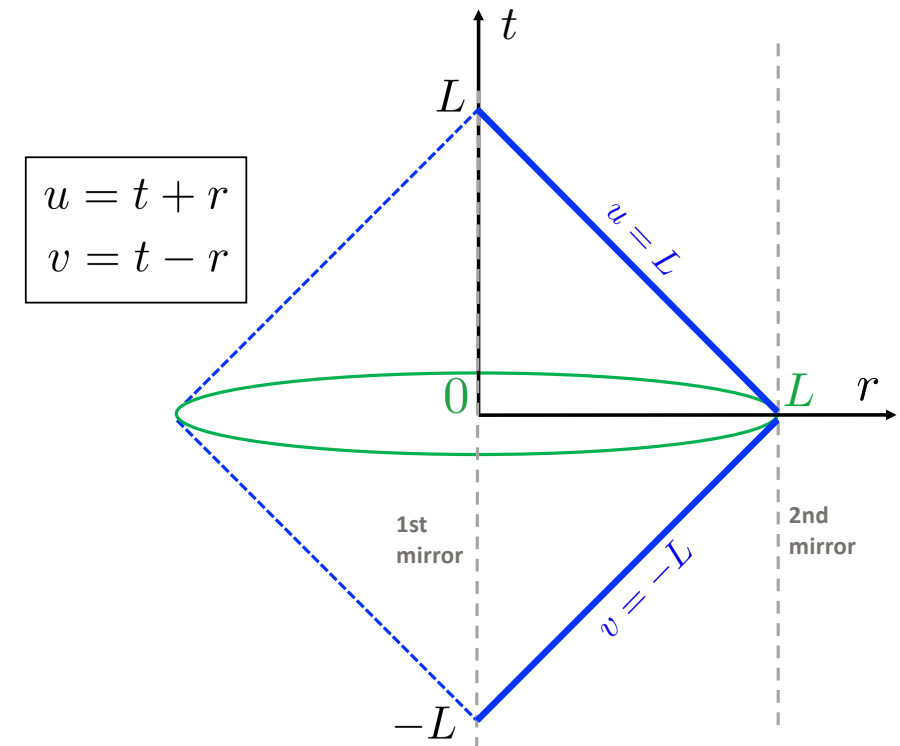


WHAT ARE WE TESTING?

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

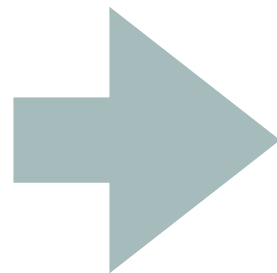
$$X^v(y) = \tilde{\ell}_p^2 \int_{-L}^L du \int d^{d-2} y' f(y, y') T_{uu}(u, y')$$

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



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

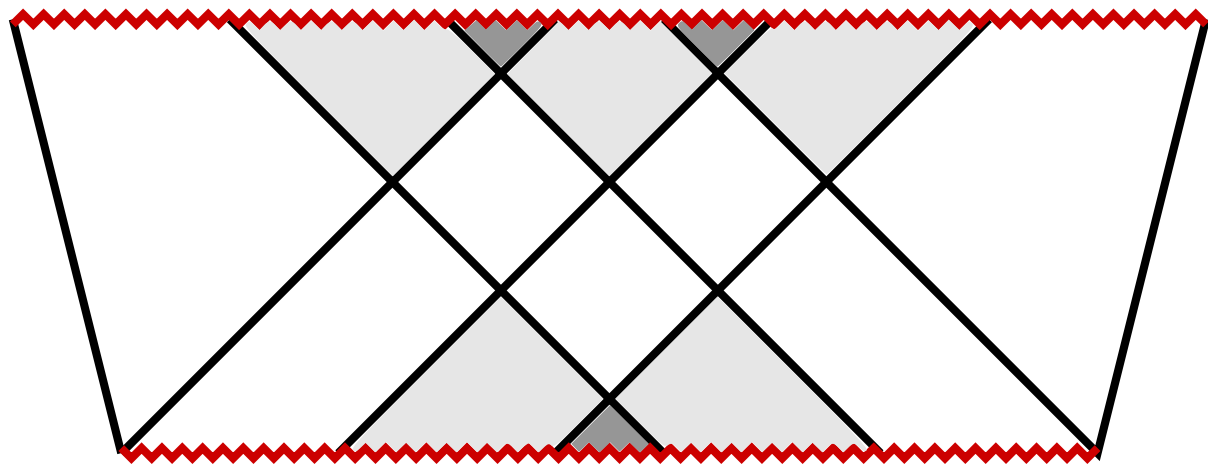
$$X^u(u, \Omega) = L - u + \delta u(u, \Omega)$$



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

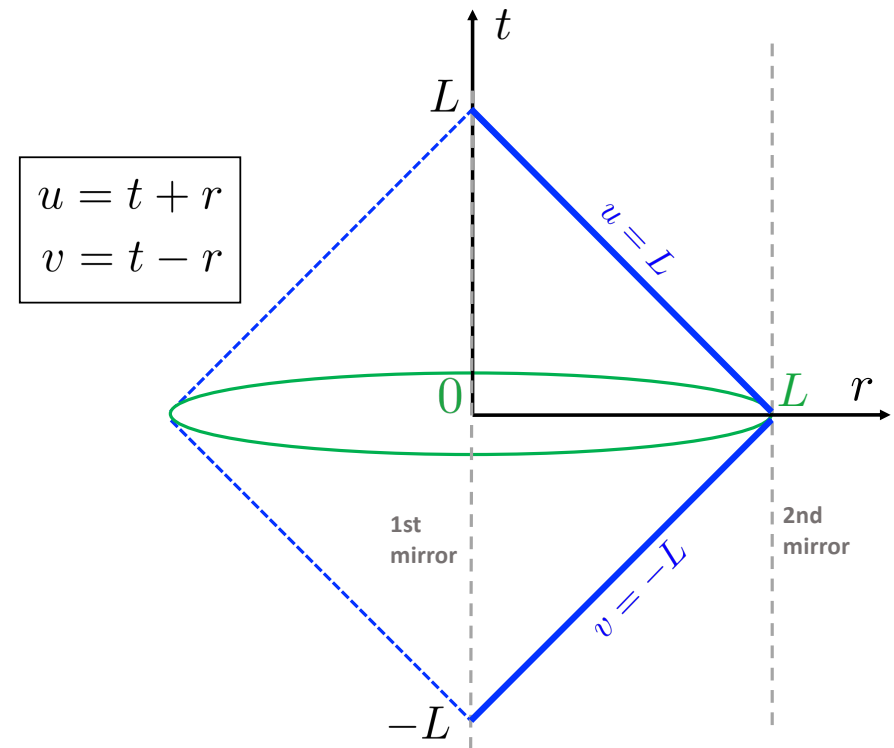
WHAT ARE WE TESTING?

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



Multiple shocks

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

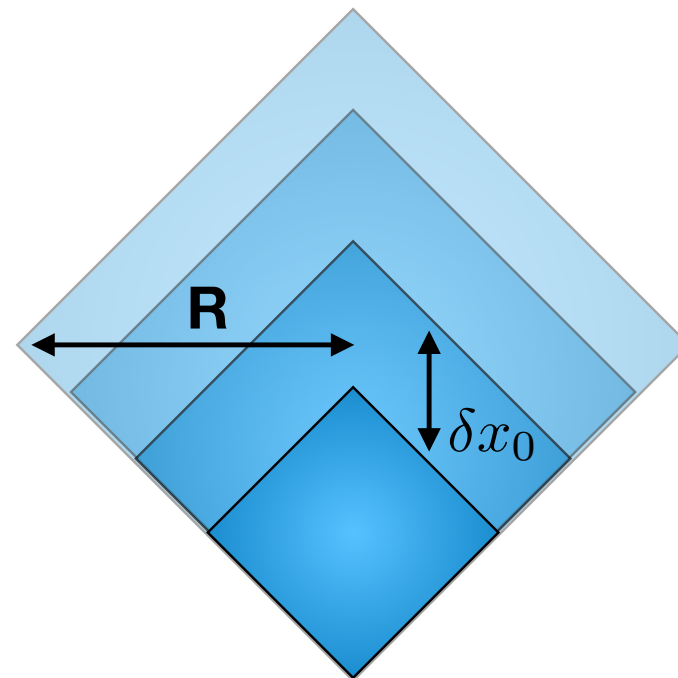
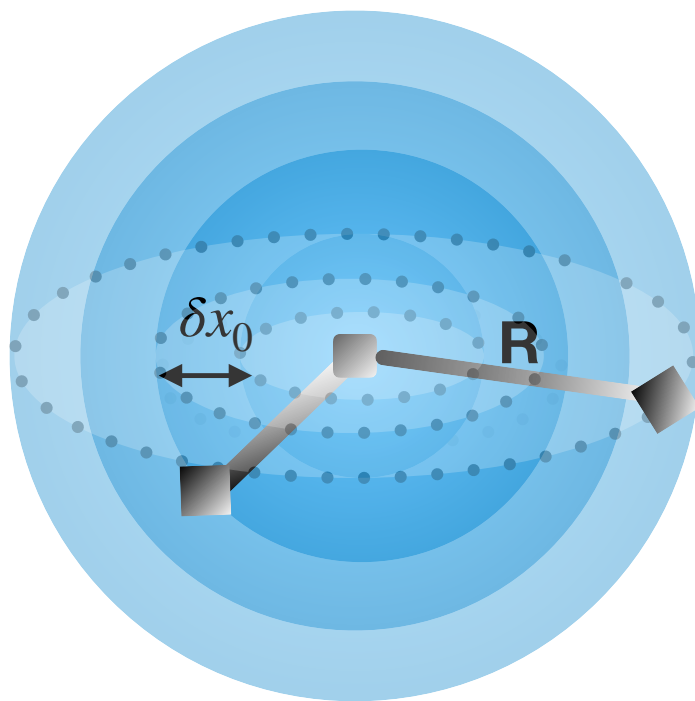


$$X^u(u, \Omega) = L - u + \delta u(u, \Omega)$$

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

WHAT ARE WE TESTING?

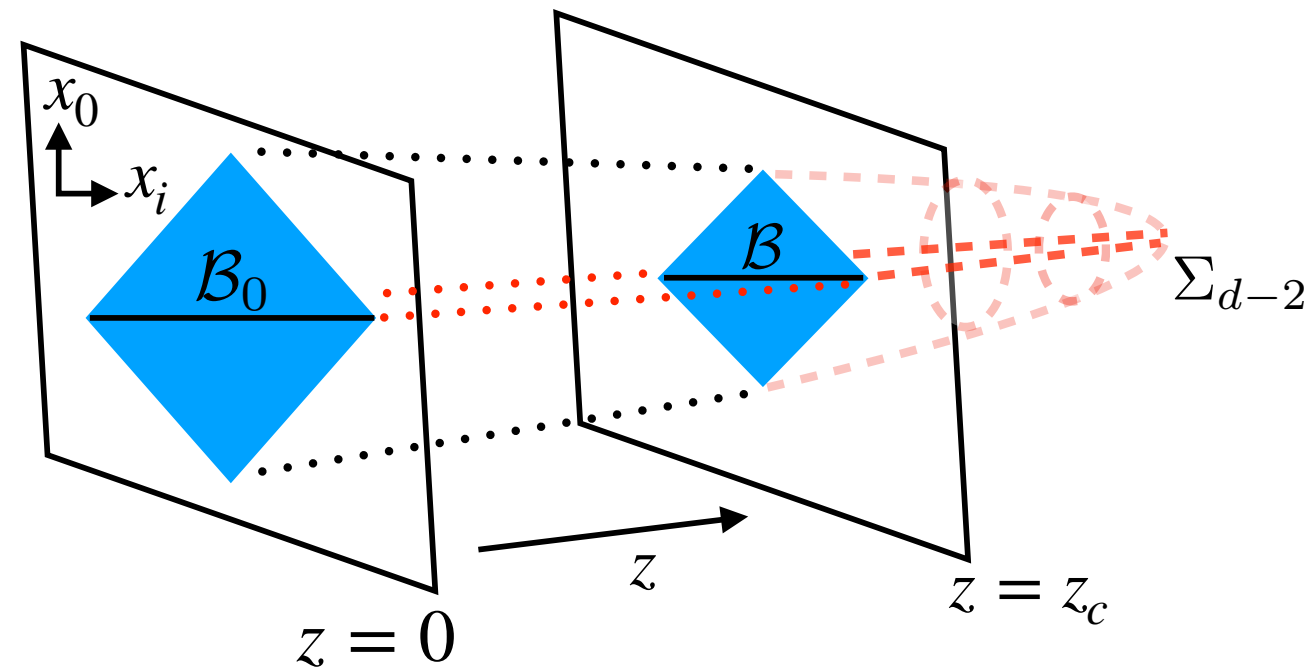
- And their Accumulation into Infrared



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

EQUIVALENT PHYSICAL DESCRIPTIONS

- In AdS/CFT, a theoretically controlled environment



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

EQUIVALENT PHYSICAL DESCRIPTIONS

► Hydrodynamics

Linearized Einstein Equation:

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

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

$$\partial_+ h^{mn} = D \nabla_a^2 h^{nm}$$

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

Banks, Keeler, KZ in progress

SIMPLE MODEL OF SPACETIME FLUCTUATIONS IN HOLOGRAPHIC QG

- The “pixellon.”
- **Bosonic** excitation whose density of states is motivated by known results in AdS/CFT
- Couple pixellon **gravitationally** to interferometer mirror and see what position fluctuations are induced
- FV allows to compute influence of bath of “**oscillators**” on “**system**” (= interferometer mirrors)

KZ 2012.05870

$$\rho_\beta = \frac{1}{e^{\beta\omega} - 1}$$

$$\beta\omega = \frac{\Delta K}{K} = \frac{1}{\sqrt{S}} \ll 1$$

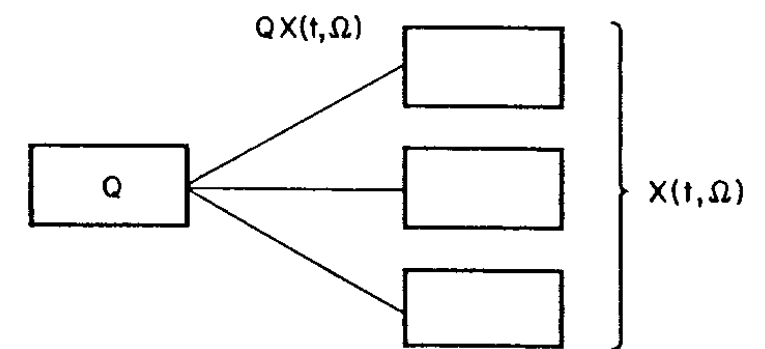
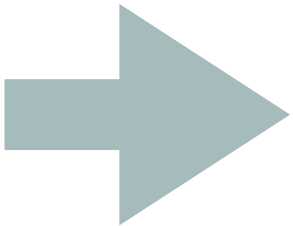
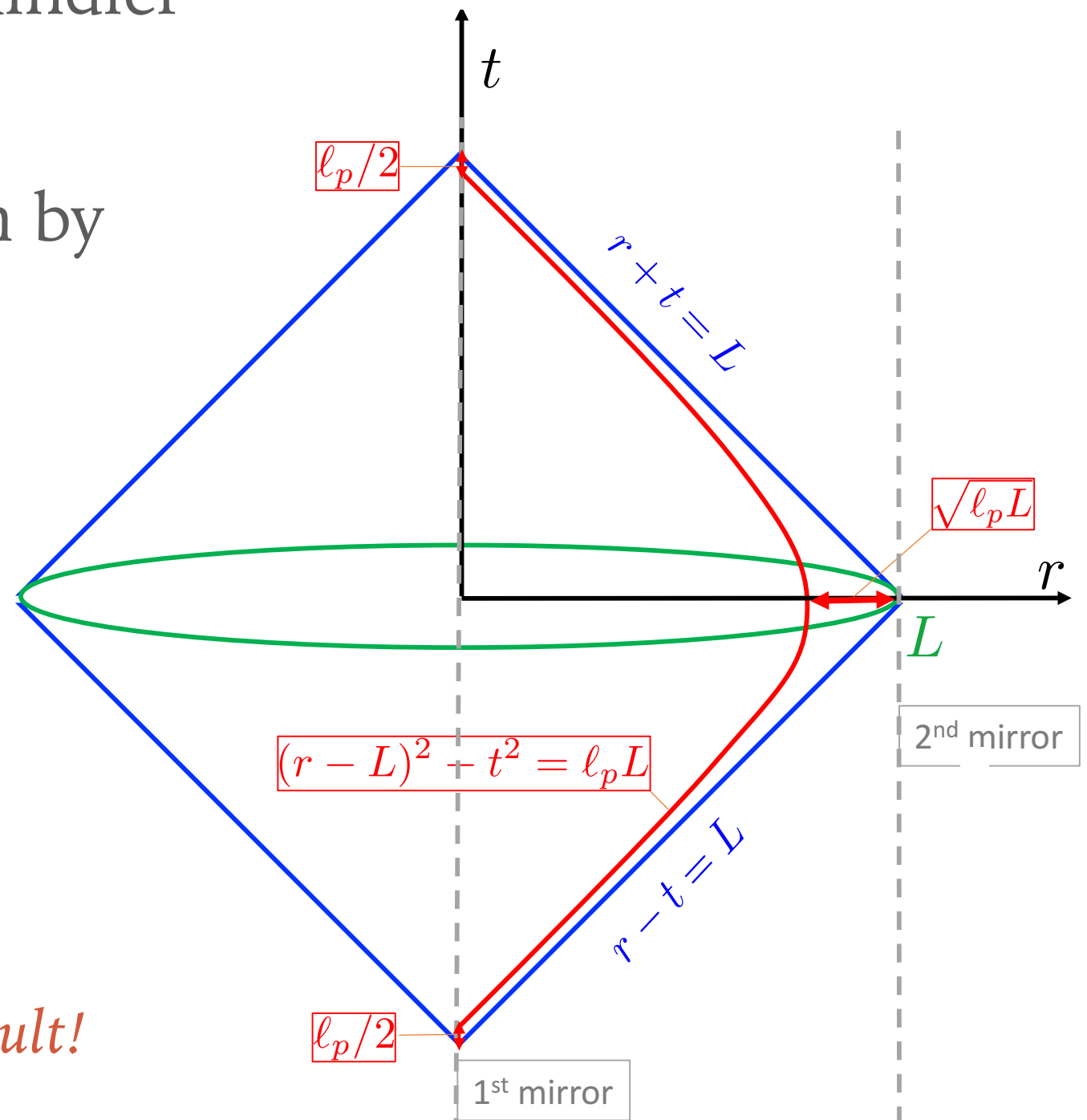


FIG. 3. Test system Q coupled to a distribution of oscillators.


$$\left\langle \frac{\delta L^2}{L^2} \right\rangle \approx \frac{al_p}{4\pi^2 L} \log \left(\frac{k_{\max}}{k_{\min}} \right)$$

EQUIVALENT PHYSICAL DESCRIPTIONS

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

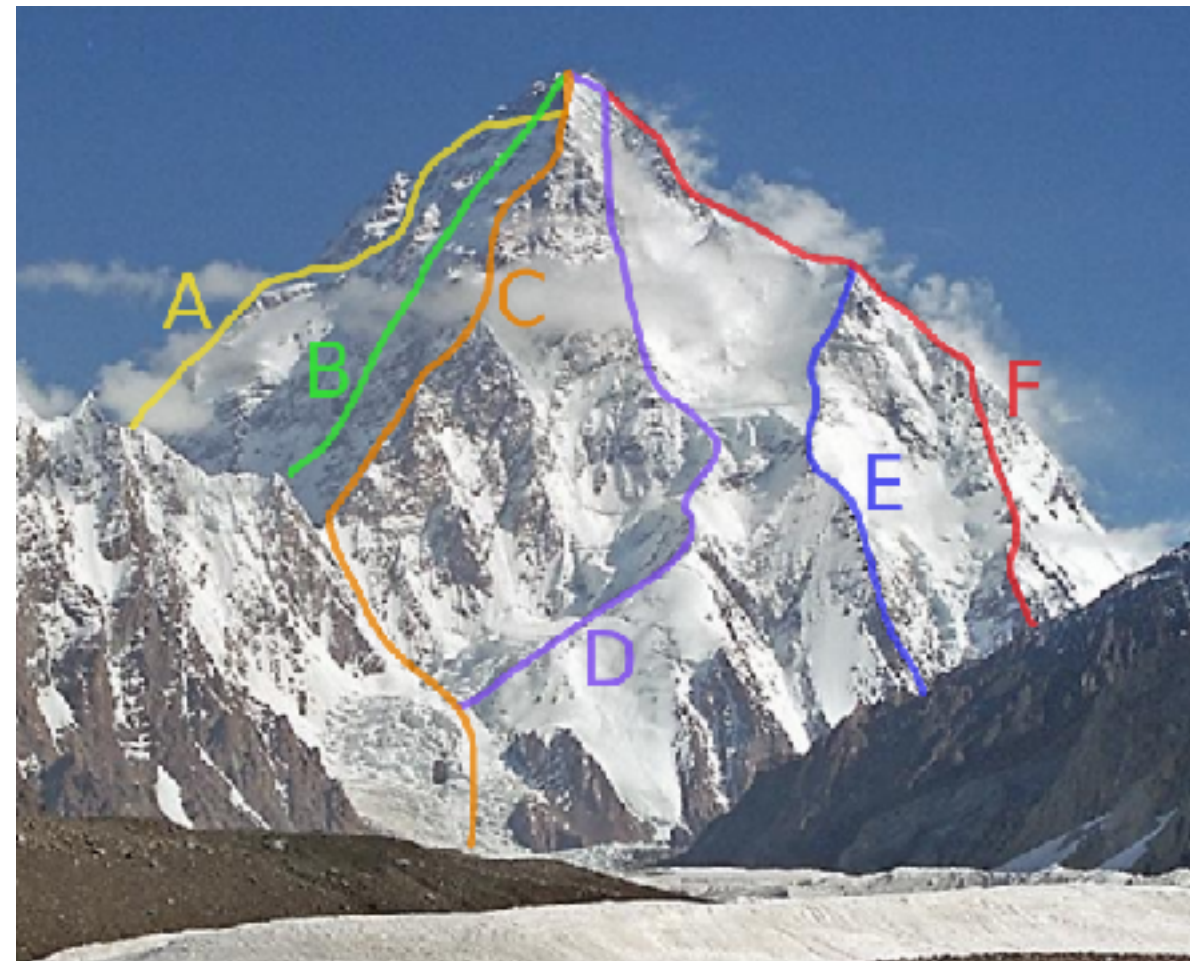


All descriptions give same result!

WHAT ROUTE TO THEORETICAL BREAKTHROUGHS DO OBSERVATIONAL SIGNATURES OFFER?

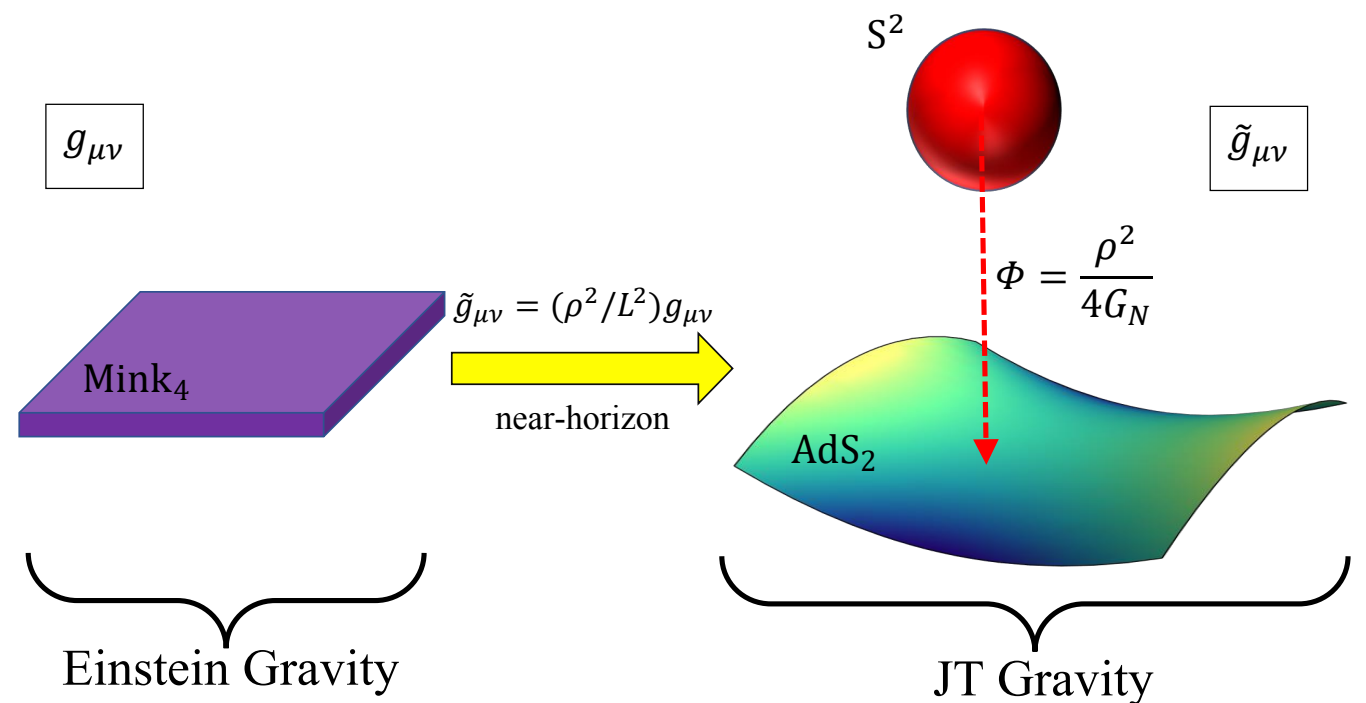
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- Utilizing **known tools** for **new questions**
 - Leads to novel approaches
 - e.g. flat space holography
 - e.g. bulk reconstruction
 - Creating a new dictionary
- What is the simplest description?
- Experiments sharpen the theoretical mind



WHAT ROUTE TO THEORETICAL BREAKTHROUGHS DO OBSERVATIONAL SIGNATURES OFFER?

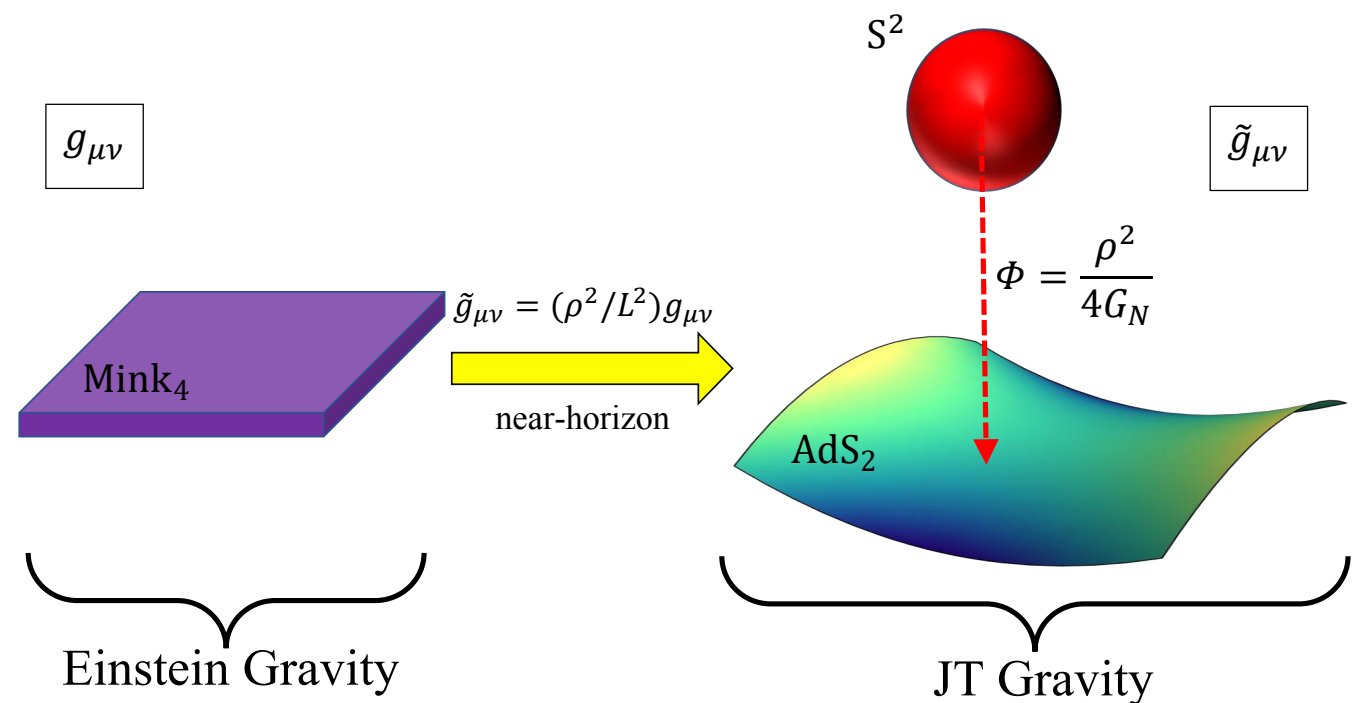
- Utilizing **known tools** for **new questions**
 - e.g. in near horizon limit, 4-d Einstein-Hilbert action dimensionally reduces to Jackiw-Teitelboim gravity in 2-d



$$ds^2_{\text{Mink}} = -dt^2 + dr^2 + r^2 d\Omega_2^2 \quad \longrightarrow \quad ds^2_{\text{Mink}} = \frac{\rho^2}{L^2} \left(L^2 \frac{-dt^2 + dr^2}{r^2} + L^2 d\Omega_2^2 \right)$$

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

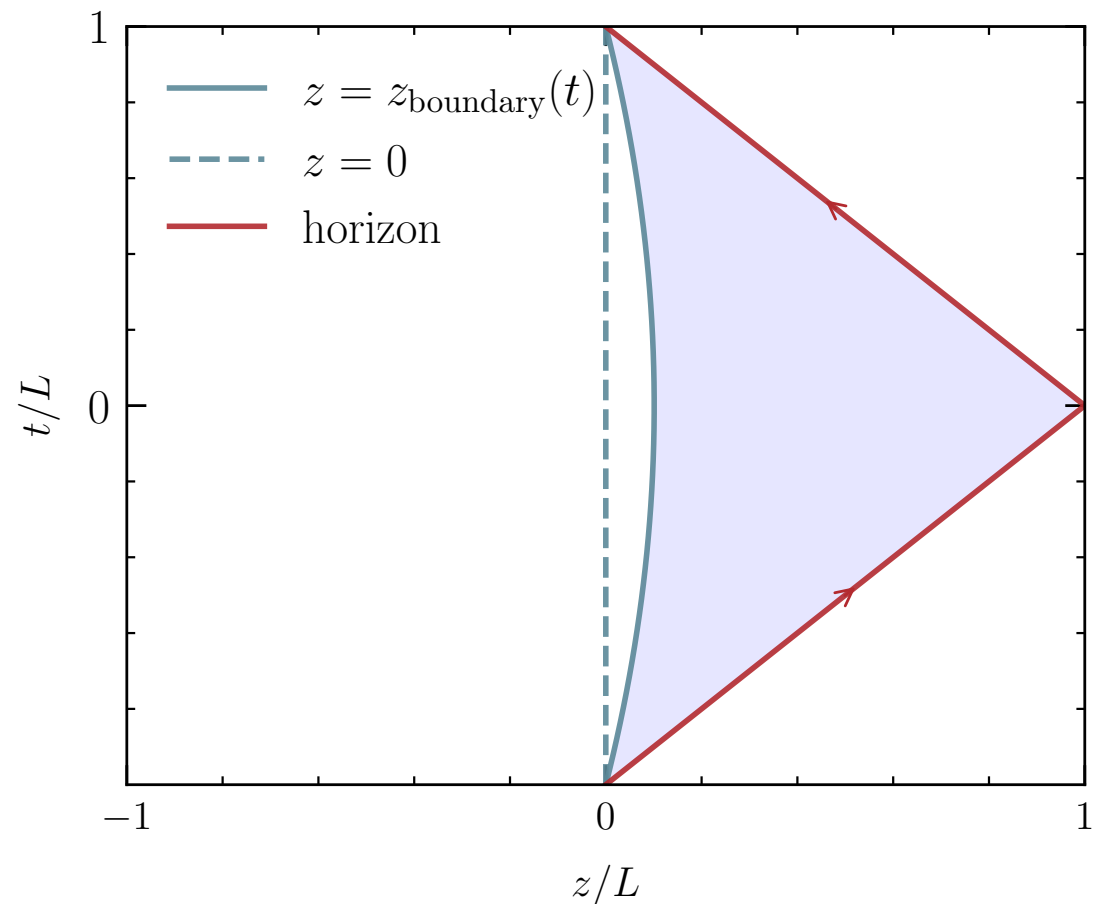


$$I = \int_{\tilde{M}_2} d^2x \sqrt{-\tilde{g}_2} \Phi \left(\tilde{R}_2 + \frac{2}{L^2} \right) + 2 \int_{\partial \tilde{M}_2} dx^0 \sqrt{-\tilde{\gamma}_1} \Phi \tilde{K}_1$$

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

$$\begin{aligned}\frac{\Delta T_{\text{r.t.}}^2}{T_{\text{r.t.}}^2} &= \frac{1}{\sqrt{2S}} \\ &= \frac{l_p}{4\pi L}\end{aligned}$$



SUMMITTING THE UNKNOWN

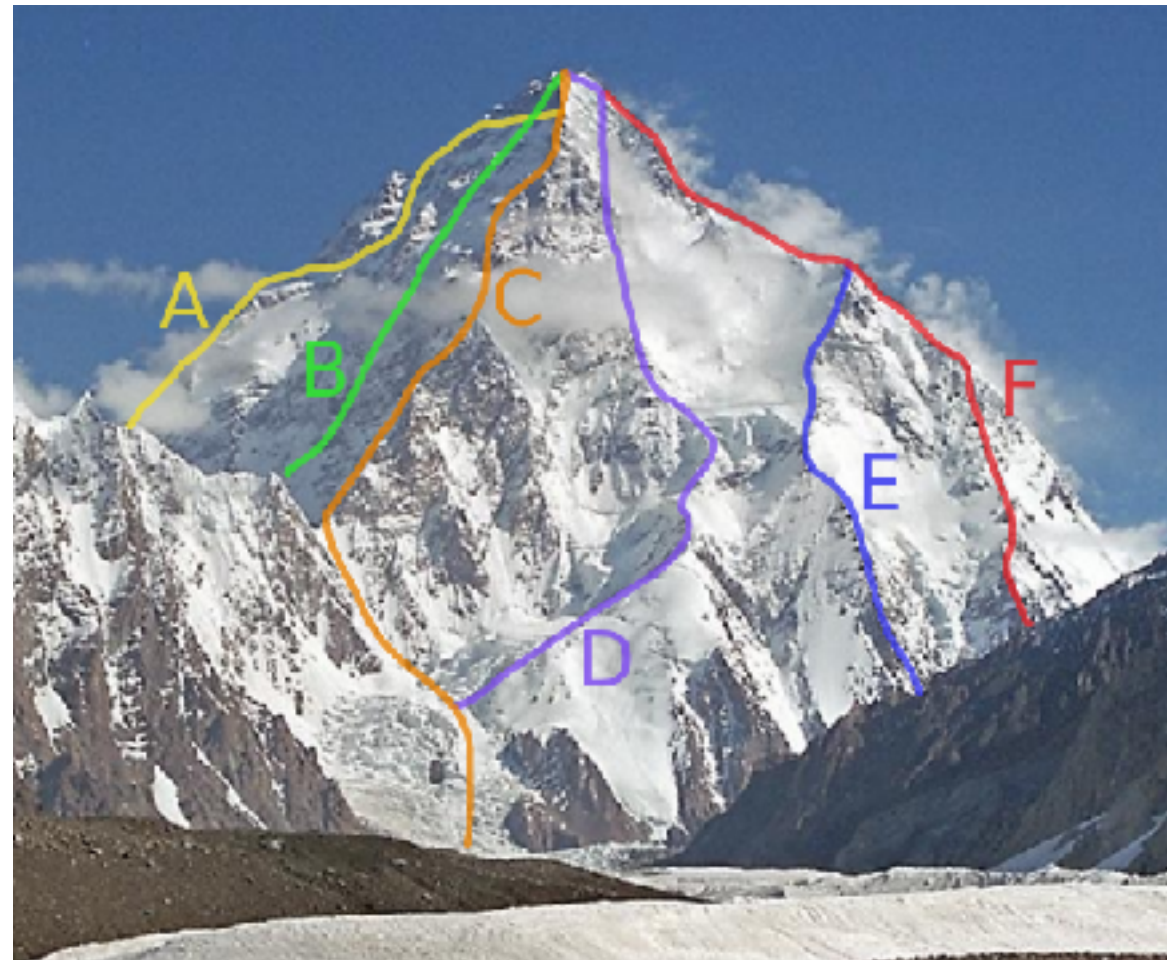
And searching for the new hydrogen atom?

Thanks Ann for you adventurous spirit and path-breaking leadership



A. AdS/CFT

B. Light Ray
Operators



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

E. Hydrodynamics EFT

C. Gravitational effective action /
saddle point expansion

D. TOCs/OTOCs